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The Pulse of Asia. Boston, 1907.
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The Climatic Factor, as Illustrated in Arid America. Washington, 1914.

B. Two books illustrating the effect of climate on man.

Civilization and Climate. New Haven, 1915.
World Power and Evolution. New Haven, 1919.

C. Five books illustrating the general principles of Geography.

Asia: A Geography Reader. Chicago, 1912.
The Red Man's Continent. New Haven, 1919.
Principles of Human Geography (with S. W. Cushing). New York, 1920.
Business Geography (with F. E. Williams). New York, 1922.
Commercial and Industrial Geography (with S. W. Cushing). Yonkers, 1923.

D. A companion to the present volume.

Climatic Changes: Their Nature and Causes (with S. S. Visher). New Haven, 1922.

EARTH AND SUN

AN HYPOTHESIS OF WEATHER AND SUNSPOTS

BY

ELLSWORTH HUNTINGTON

RESEARCH ASSOCIATE IN GEOGRAPHY
IN YALE UNIVERSITY

WITH A CHAPTER BY H. HELM CLAYTON

FORMERLY OF THE ARGENTINE
WEATHER SERVICE

NEW HAVEN
YALE UNIVERSITY PRESS
LONDON • HUMPHREY MILFORD • OXFORD UNIVERSITY PRESS
MDCCCCXXIII

QC883
.H94

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27 December 1947 5.00

THE THEODORE L. GLASGOW MEMORIAL PUBLICATION FUND

THE present volume is the sixth work published by the Yale University Press on the Theodore L. Glasgow Memorial Publication Fund. This foundation was established September 17, 1918, by an anonymous gift to Yale University in memory of Flight Sub-Lieutenant Theodore L. Glasgow, R.N. He was born in Montreal, Canada, and was educated at the University of Toronto Schools and at the Royal Military College, Kingston. In August, 1916, he entered the Royal Naval Air Service and in July, 1917, went to France with the Tenth Squadron attached to the Twenty-second Wing of the Royal Flying Corps. A month later, August 19, 1917, he was killed in action on the Ypres front.

TO

THE BROTHER AND SISTER

WHOSE APPRECIATIVE HELP HAS FOR YEARS
BEEN AN INCENTIVE TO STUDIES
OF THE EARTH AND SUN

PREFACE

THIS book and its companion, *Climatic Changes,* were originally written as parts of a single volume. That volume, which began as a short article, grew to such proportions that it seemed wise to divide it. The division was logical and desirable because the part which is here published deals with the present, while *Climatic Changes* deals primarily with the past. Both parts were originally ready for the printer at the same time, but while *Climatic Changes* was being put in type, it seemed advisable to revise certain parts of *Earth and Sun.* That revision, as usually happens, involved much more work and time than was at first expected. Hence, although the present volume logically precedes the other, it is published later.

The part of this book which has received most attention since the original manuscript was completed has been the chapters dealing with the electrical relations of the earth and sun. Each successive step seems to point more and more clearly to an important solar effect upon atmospheric electricity as well as upon barometric pressure and storms.

The bearing of this conclusion upon modern studies of meteorology and climate may be gathered from the present book; its bearing on the hypotheses set forth in *Climatic Changes* requires a brief explanation. The main idea of that book is that climatic changes depend partly on terrestrial conditions, such as the form and altitude of the lands, the frequency of volcanic eruptions, and the chemical or physical composition of the atmosphere and ocean, and partly on changes in the activity of the sun. The solar changes are believed to act chiefly through variations in barometric pressure and especially in the number, location, and intensity of cyclonic storms. The verity of this main idea is independent of whether the sun influences the upper air through ordinary radiation, in the form of light and heat, through electronic emissions, or through both.

A secondary idea set forth in *Climatic Changes* is that variations in solar activity are intimately connected with the relation of the sun to the positions and distances of the planets and of other heavenly bodies such as the stars. This hypothesis neither stands nor falls with any special hypothesis as to how the sun influences the earth. But each of the surprising coincidences which this book describes between the atmospheric activities of the sun and the earth adds to the probability that the atmosphere of the sun is influenced by other heavenly bodies, both planets and stars.

In preparing the present volume, I have been most effectively assisted by an even broader circle of friends than in *Climatic Changes*. Professor Frank Schlesinger of the Yale Observatory has been constantly consulted about the astronomical problems of the book. The same is true of my colleague, Professor Leigh Page, in respect to problems in physics, while the late Professor Henry S. Bumstead was equally helpful. Two other colleagues, Professor Charles Schuchert and Professor Ernest W. Brown, have also played an important part in criticising and perfecting the book. In the domain of meteorology five men have been especially helpful. Professor Charles J. Kullmer of Syracuse University has prepared a most significant series of maps of storm frequency which are an indispensable foundation of important parts of this book. He has put them freely at my disposal and many are here published for the first time. Mr. H. Helm Clayton, formerly of the Argentine Weather Service, has criticized not only the manuscript but the proof. Mr. Clayton has likewise contributed a chapter. His book on *World Weather* (Macmillan Co., 1923) is a notable contribution to science; it bids fair to be a powerful agent in causing an almost revolutionary change in the accepted ideas as to the causes of the weather. Professor Stephen S. Visher of Indiana University has actively coöperated in the first half of the book, and has made many most valuable suggestions in the later parts. Professor Charles F. Brooks of Clark University has likewise criticized the manuscript and large sections of the proof. Mention should also be made of the assistance of Professor W. J. Humphreys of the United States Weather Bureau. Although he radically disagrees with certain conclusions of this book, he has repeatedly called attention to matters which might otherwise have escaped attention. Another to whom thanks are due is Dr. Ernst Antevs, who has suggested several points which appear in this book.

The friends here mentioned have by no means been easy critics. Each of them has made suggestions that have necessitated long and laborious work. In many cases I have expressed views with which one or another does not wholly agree, but in no case have the suggestions of my co-workers failed to cause some change in the text of this book. The greater my experience in writing books and in securing the assistance of others, the more I am impressed with the innate spirit of kindliness and coöperation which pervades the scientific men of America.

In addition to all these, Miss H. Charlotte Hall has cheerfully worked overtime and faithfully checked up many errors, verified many facts, and prepared the index.

Last, but far from least, my brother and sister have for many years assisted in a most fundamental fashion. The purely clerical work involved in preparing this book has cost several thousand dollars, much of which they have supplied. Few people who have not engaged in statistical work realize the weeks or months of labor that may be needed for a single curve or a single series of correlation coefficients. Still fewer know how disheartening it is for the investigator to realize the necessity for such labor but to be unable to undertake it for lack of time and money. And fewest of all know how encouraging it is to have friends or kindred who volunteer to help because they have faith that honest work cannot be wholly fruitless.

New Haven, Conn.,
May, 1923.

NOTE ON *CLIMATIC CHANGES*

IN *Climatic Changes* it is stated that Alpha Centauri is receding from the sun after having made its closest approach about 28,000 years ago. Dr. Edison Pettit of the Mount Wilson Observatory has called my attention to the fact that this is a mistake. Alpha Centauri is approaching the sun, not receding. The mistake arose in this way. On page 57, volume 7 of the Bulletin of the Lick Observatory, a publication noted for its accuracy, the sign for one of the motions of Alpha Centauri is printed as plus instead of minus, but this fact was not detected in time to be included in the list of errata. Accordingly this wrong sign was used in computing a table published by Dr. C. L. Stearns in *Popular Astronomy,* volume 30, page 97, and reproduced on pages 276 and 277 of *Climatic Changes.* So far as the main hypotheses set forth in *Climatic Changes* are concerned, the mistake in the Lick Bulletin is of no importance, as may be judged from the following quotation:

"The fact that Alpha Centauri, the star which would be expected most strongly to influence the sun, and hence the earth, was nearest the sun at the climax of the last glacial epoch, and that today the solar atmosphere is most active when the star is presumably most disturbed may be of no significance. It is given for what it is worth." (*Climatic Changes,* p. 282.)

Since Alpha Centauri is approaching the sun rather than receding, the words "was nearest the sun at the climax of the last glacial epoch" ought to be changed to "will be nearest the sun some 28,000 years hence." Corresponding changes are necessary in other parts of the discussion of Alpha Centauri, but not in what is said as to the fact that the sunspot maxima at present are high during the times when the two parts of Alpha Centauri are approaching one another. It likewise still remains true that so far as the motions and distances of the stars are known, no brilliant or double stars have been at a minimum distance from the sun since about 24,000 years ago, nor will any be at a minimum distance for about 17,000 years in the future. On the other hand, between 24,000 and 49,000 years ago, that is, during the period presumably covered by the last advance of the ice, five stars are known to have been at a minimum distance from the sun. All five, because of their magnitude as seen from the earth or because of being double, would be expected to have more effect upon the sun's atmosphere than any of the seven known stars which have been or will be at a minimum distance between 24,000 years ago and 17,000 years hence. From 17,000 to 34,000 years in the future, at least seven other stars will reach their minimum distance from the sun. Five of these, including Alpha Centauri, are double, and all seven are of such magnitudes that they would be expected to be more effective than any star arriving at its minimum distance from the sun between 24,000 years ago and 17,000 years in the future. Thus so far as the stars are known, there is nothing inconsistent with a glacial epoch twenty-five to forty thousand years ago and an interglacial epoch now. So far as the stars are concerned, the stage seems also to be set for another and more severe glacial epoch twenty or thirty thousand years hence.

In our present incomplete state of knowledge I attach very little importance to this. As I have stated in *Climatic Changes,* Dr. Frank Schlesinger, Director of the Yale Observatory, under whose direction Dr. Stearns' table was prepared, has especially impressed upon me the fact that moving stars whose near approach to the earth may not be more than a hundred thousand years away in the past or future may now be so distant that they are not included in the table. Their motions may not even be known. This whole discussion proves nothing as to a stellar hypothesis of glaciation. It merely shows that so far as the movements of the stars are yet known they do not contradict the hypothesis that the stars may influence the sun's atmosphere and thus cause changes of climate upon the earth. The mistake in the Lick Bulletin is unfortunate, but it has no bearing on the truth or falsity of the hypothesis that solar disturbances cause changes of terrestrial weather, and that the sun's atmosphere may somehow be disturbed by the near approach of stars.

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CHAPTER I

SOLAR DISTURBANCES AND TERRESTRIAL TEMPERATURE

ONE of the outstanding problems of science is the causes of cyclonic storms and of other conditions which give rise to variations of weather from day to day and year to year. Another problem is the causes of the great climatic changes of the past, such as glacial periods. The solution of both problems would presumably lead to the desirable goal of ability to predict variations in both weather and climate far in advance. Formerly there was a strong tendency to regard variations of the weather and changes of climate as distinct phenomena due to different causes. The facts set forth in this book and in its companion volume, *Climatic Changes*,[1] suggest that there is no sharp line between them. Weather is a temporary condition due to a complex combination of temperature, atmospheric pressure, winds, atmospheric moisture, convection, cyclonic storms, and precipitation: climate is merely the average weather for a long period. A change of climate means merely that one or more of the factors which combine to make the weather has suffered some more or less permanent change.

The main hypotheses as to the causes of both climate and weather fall into two great types. One type appeals mainly to terrestrial causes, while the other appeals to solar or cosmic causes. A brief and not strictly chronological statement of some of the chief hypotheses advanced in explanation of glaciation during geological times will illustrate the matter. One of the first glacial hypotheses was Croll's suggestion that because of the precession of the equinoxes the earth is sometimes nearest the sun in the northern summer and sometimes in the northern winter, as at present. Moreover, the distance between the earth and sun varies, for the earth's orbit is more eccentric at some times than at others. This solar or cosmic hypothesis may be contrasted with the purely terrestrial view that glaciation is due mainly to deformation of the earth's crust and consequent changes in the form of the lands and in ocean currents. An early solar hypothesis, on the other hand, was the untenable supposition that glaciation arises from a cooling of the sun and a chilling of the earth. Next, the pendulum of thought swings back to the earth with the hypothesis that changes in the amount of carbon dioxide in the air alter the percentage of the sun's heat that can be retained by the atmosphere. This last idea helped to generate another solar hypothesis, namely, the supposition that glaciation arises from increased solar radiation whereby evaporation in equatorial regions is augmented so much that great cloud caps are formed in higher latitudes, thus keeping out the sun's heat and permitting ice to accumulate.

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[1] Climatic Changes: Their Nature and Causes, by Ellsworth Huntington and Stephen S. Visher, Yale University Press, New Haven, 1922.

Since 1910, Humphreys, Abbot, and Fowle have swung the pendulum back toward the earth by their studies of the effect of volcanic dust in shutting out the sun's radiation. Taylor, on the other hand, has suggested a sweeping cosmic hypothesis to the effect that if the solar system should approach another similar system in its flight through space, the increased gravitative force would retard the earth's rotation and thereby diminish the strength of the atmospheric circulation and cause glaciation. The slower rotation might also lessen the bulge at the equator, thus causing deformation of the earth's crust and the formation of mountains. Although this interesting hypothesis may not accord with the findings of astronomers and physicists, it has the distinction of being the first which suggests a single cause for climatic changes and for the movements of the earth's crust which frequently occur at the same time. Another recent hypothesis is that of Manson and Knowlton, who attempt to swing the pendulum back to the earth. They hold that the main control of climate is the earth's internal heat. Throughout most of the earth's history such heat is supposed to have kept the oceans warm so that the earth was covered with a blanket of cloud which made the climate relatively uniform in all regions. The final cooling of the earth in Pleistocene times is supposed to have led to the last glacial period, but earlier glacial periods are largely ignored or minimized.

In *Climatic Changes* an attempt has been made to sum up the more important hypotheses of glaciation, and to give each its due weight. A new hypothesis has been presented ascribing certain kinds of climatic changes to variations in the number, intensity, and position of cyclonic storms arising from variations in the sun's atmosphere, but terrestrial causes are also given a prominent place.

Many other hypotheses have been advanced to explain climatic changes, but enough have been mentioned to show how strongly the terrestrial and the solar or cosmic ideas have been contrasted. As a matter of fact it is almost certain that no single hypothesis explains all the varied phenomena of climatic changes. Astronomy has proved beyond question that the distance between the earth and the sun varies from season to season and also from century to century and millennium to millennium. Hence there must be a certain amount of truth in Croll's hypothesis. Again, it is practically certain that the amount of energy received from the sun varies slightly from day to day, and it is highly probable that during longer periods the variations are greater than is yet evident from accurate records. Again a veil of volcanic dust evidently shuts out some solar energy and must have a climatic effect. The size and elevation of the continents, the direction and height of mountains, and the strength and volume of ocean currents are all of primary importance in determining the climatic conditions of any given part of the earth. Thus it appears that many causes are producing climatic changes, while there may be still others as yet unknown. The problem of the climatologist is to find out in what way and to what extent each cause plays its part.

In explanation of the variations of the weather there is no such array of hypotheses as in the case of glaciation. There are, however, two main lines of thought. One group of students emphasizes the fact that storms, cold waves, floods, droughts, and all other types of weather depend largely upon accidental combinations of terrestrial conditions. They point out that the air is always more or less turbulent, as anyone can see on a hot day. One area becomes warm more rapidly than another, and there the air begins to rise, while winds blow in from the sides, clouds are formed, rain may fall, and certain parts of the earth's surface are cooled. The other school recognizes the great importance of these accidental variations, but does not believe that they can produce such great and prolonged effects as are seen in the many cycles of weather which last anywhere from a few days to several decades. In spite of numerous perplexing and seemingly contradictory phenomena, the evidence leads them to emphasize the importance of variations in the amount or kind of energy received from the sun as the cause of many of the chief irregularities of the weather.

Obviously, then, one of the main problems to be settled in respect to both climate and weather is the degree of effect of the sun's variations upon those of the earth. This problem, as it affects climate, is discussed in *Climatic Changes;* as it affects weather it is the main theme of the following pages. Both books assume that the effects of purely terrestrial conditions upon climate and weather are so strong and so well known that in a book of this kind they require relatively little discussion. On the other hand, the effect of variations in solar activity is still so incompletely understood that it requires full discussion. Hence we shall devote ourselves almost entirely to an attempt to unravel part of the tangled skein of the relation between variations in the atmospheres of the sun and earth.

One of the first difficulties that confronts us is the lack of any absolute measurements of solar activity. In many respects the most perfect measurements of solar activity are expressed in terms of the so-called solar ''constant,'' which is really a variable, and which may be defined as a measure of solar radiation so far as the degree of radiation can be calculated from its effect in producing heat. Unfortunately, however, not till about 1905 is even an imperfect and incomplete record of the solar constant available. Moreover, the solar constant measures only those kinds of solar radiation which, in part at least, penetrate the air and are converted directly into heat on reaching the earth's surface; it does not measure the unknown amount of energy belonging to wave lengths or other forms of energy which fail to penetrate the upper air. Nor do the published records separate the different wave lengths, although short waves may have quite diverse meteorological effects from long waves. In addition to all this the solar constant by its very nature cannot measure the electrons, the electrical waves, and the magnetic waves sent from the sun.

If an attempt is made to measure the activity of the sun's atmosphere in other ways, and thus to judge of its probable nonluminous radiation, the difficulties are quite as great as with the solar constant. The most obvious disturbances of the solar atmosphere are sunspots, but solar prominences, faculæ, flocculi, and magnetic activity are all measurable, and are all evidences of disturbance and of changes in the kind or amount of energy emitted by the sun. To a certain degree each of these pursues its own course, but fortunately the general progress of all types of solar activity, including ordinary radiation, is similar, except, perhaps, near sunspot minima. Since the sunspot records are far more complete than those of any other solar variation, they are taken in this volume as the chief measure of solar activity. Their nature is discussed later in Chapter X. The sunspot numbers, to which reference will again and again be made, were originally prepared by Wolf and have been revised and continued by Wolfer.[2] The outstanding feature of the sunspot numbers is that they are based partly on the actual number of spots and partly on the size of the spots. The determination of the numbers is now based on photographs of the sun's disk taken daily at several observatories. The actual areas of the spots for each day are published by the Greenwich Observatory and are used in many of the calculations in this book. In general the sunspot numbers and areas vary in rather close harmony. Data for the areas, however, do not extend back nearly so far as those for the numbers, which are available in imperfect form as far back as 1755.

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[2] These numbers have been published in various places, one of the most accessible being the Monthly Weather Review, April, 1902, August, 1920, and January, 1923.

In studying the relation between solar and terrestrial activity investigators have been hampered not only by the difficulty of finding a reliable means of measuring the sun's activity, but also by the difficulty of determining what areas and what phenomena should be considered upon the earth. As Hann[3] has pointed out, the solar relationship, if such there is, may be concealed by accidental terrestrial conditions, which play a large part in the ordinary types of weather. Such concealment is especially common when only a small part of the earth's surface is studied. On the other hand, if the average conditions of the whole earth in any respect are compared with the activity of the sun's atmosphere, a real relationship may be concealed, for the earth's response to the sun seems to vary according to the type of climate. Hildebrandsson[4] has shown that the atmosphere contains centers of two kinds which act in opposite ways, the pressure, for example, rising in one set while it falls in the others. Later students, especially Helland-Hansen and Nansen,[5] have amplified this conclusion and extended it to details of temperature as well as pressure. They show that the areas of positive and negative changes vary in size and shift irregularly so that the intermediate areas are sometimes under the influence of one type and sometimes of another. Thus if a single small area is considered there may be all sorts of contradictions between solar and terrestrial conditions. If the whole earth is studied, the variations in one direction may largely neutralize those in another direction. Yet when a central area of one distinct climatic type is investigated, it may give evidence of strong solar relationships. A well-developed example of this kind will be given in Chapter II, where we shall study the distribution of storms in the United States.

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[3] J. Hann: Handbuch der Klimatologie, Stuttgart, 1908-1911, 3d ed., 3 vol.

[4] H. H. Hildebrandsson: Quelques recherches sur les centres d'action de l'atmosphere, Kong. Svenska Vetenskaps-Akademiens, XXIX, No. 3, 1897; XXXII, No. 4, 1899; XLV, No. 2, 1909; XLV, No. 11, 1910; LI, No. 8, 1914.

[5] B. Helland-Hansen and F. Nansen: Temperatur-schwankungen des Nord-Atlantischen Ozeans und in der Atmosphäre, 1917. Reprinted with additions in Vol. 70, No. 4, Smiths. Misc. Coll., 1920, under the title "Temperature Variations in the North Atlantic Ocean and in the Atmosphere."

Another serious difficulty is that a number of climatic phenomena act as though the sun exerted a certain kind of influence when the sunspots are most numerous, and again to a less degree when the spots are at a minimum. For example, Hann[6] recapitulates several investigations which show a major maximum of rainfall at sunspot maxima, and a minor maximum of rainfall at sunspot minima. Helland-Hansen and Nansen[7] point out such relationships repeatedly. In the same way Douglass,[8] in his studies of climatic cycles as recorded in tree growth, believes that he has found not only a cycle corresponding to that of the sunspots, but also a smaller cycle of half the sunspot period. In an investigation of barometric pressure over the North Atlantic Ocean, I found a similar condition.[9] The steepness of the barometric gradients, that is, the degree of difference in pressure in a given distance, generally varies in harmony with the sunspots, but just previous to the rise of a new series of spots, the gradients increase somewhat as at sunspot maxima, although to a less degree. In an unpublished study of the departures of rainfall from the normal I have found a somewhat similar condition. On the basis of 154 stations distributed all over the world,[10] it appears that a slight excess of rainfall begins with the year of minimum spots and continues during periods of increasing sunspots, while a deficiency begins with the year of maximum spots. The solar constant, so far as data are yet available, seems to show a minor maximum at times of few sunspots or when a new sunspot cycle is beginning. This suggests that if fuller data were available, many of the puzzling discrepancies between solar and terrestrial activity would disappear.

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[6] *Loc. cit.*

[7] *Loc. cit.*

[8] A. E. Douglass: Tree Growth and Climatic Cycles, Carnegie Institution, Washington, 1919.

[9] Ellsworth Huntington: Solar Disturbances and Terrestrial Weather, Mo. Weath. Rev., March, April, and June, 1918; Vol. 46, pp. 123-141, 168-177, and 269-277.

In view of all the circumstances which tend to obscure whatever relationship there may be, it is not surprising that there has been much difficulty in unraveling the tangled skein of the connection between the atmospheres of the earth and the sun. Nevertheless, certain fundamental relationships seem now to be almost proved.[11]

Three climatic elements, temperature, storms, and barometric pressure, will serve to show how the sun's changes are related to those of the earth. We shall begin with temperature because that is the element which is usually taken as the foundation of the others. We shall find, however, that barometric pressure may be an almost equally fundamental variable, and that its variations may give rise not only to storminess, but to changes in temperature. Various investigators, especially Köppen, and at a later date the famous astronomer, Simon Newcomb,[12] have found unmistakable evidence of a world-wide variation in temperature in harmony with the sunspot cycle. In Köppen's[13] final investigation, he studied the matter with great thoroughness for a period of one hundred years. Using all available records during the earlier decades and representative records in all parts of the world during the later periods, he determined the extent to which the earth's temperature departs from the normal each year. The twenty million observations which he thus summarizes show beyond question that during the last century the earth was relatively warm during periods of sunspot minima and cool at times of maxima. The difference is greatest, 0.6°C., in equatorial latitudes, and diminishes in temperate latitudes, where it averages 0.4°C. At present either extreme lasts so short a time that it is of slight importance. Nevertheless, the difference between the earth's mean temperature at sunspot maxima and minima during the nineteenth century was approximately one-twelfth of the supposed difference between the temperature at the height of the glacial period and now.

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[10] G. T. Walker: Sunspots and Rainfall, Mem. Ind. Meteor. Dept., Vol. XXI, Pt. A, 1915.

[11] A full discussion of the whole subject is found in the English translation of the work of Helland-Hansen and Nansen, published by the Smithsonian Institution (Misc. Coll., Vol. 70, 1920). That volume contains a full bibliography and an historical résumé dating back to 1651 when "the Jesuit Father Riccioli announced that with a decrease of the sunspots the temperature of the earth increases and with an increase of them it diminishes," a conclusion which is now almost universally accepted. The main conclusion of Helland-Hansen and Nansen agrees with that which Bigelow and the Lockyers had previously announced, namely, that "variations in the solar activity play a very great part in variations in air pressure, temperature, and precipitation, and—that *it is the air pressure distribution which in the first place is influenced* and produces its secondary actions on all the other meteorological elements" (p. 243). (Italics mine.)

Humphreys[14] and also Abbot and Fowle[15] have taken up this matter in detail. On the basis of a much smaller number of stations than Köppen's, they have prepared curves of terrestrial temperature which go back to 1750. In their later portions (Fig. 1) these agree essentially with Köppen's data and show clearly that the earth's temperature rises when sunspots are few and vice versa. In the earlier portions this is not so evident, presumably because the available records are few and imperfect.

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[12] Simon Newcomb: A search for fluctuations in the sun's thermal radiations through their influence on terrestrial temperature, Trans. Am. Phil. Soc., N. S., Vol. 21, 1908.

[13] W. Köppen: Luft-Temperaturen, Sonnenflecken und vulcanische Ausbruche, Meteorol. Zeitschrift, Vol. 7, 1914, pp. 303-328.

[14] W. J. Humphreys: Physics of the Air, 1920, p. 598.

[15] C. G. Abbot and Fowle: Smiths. Misc. Coll., Vol. IX, No. 29, 1913.

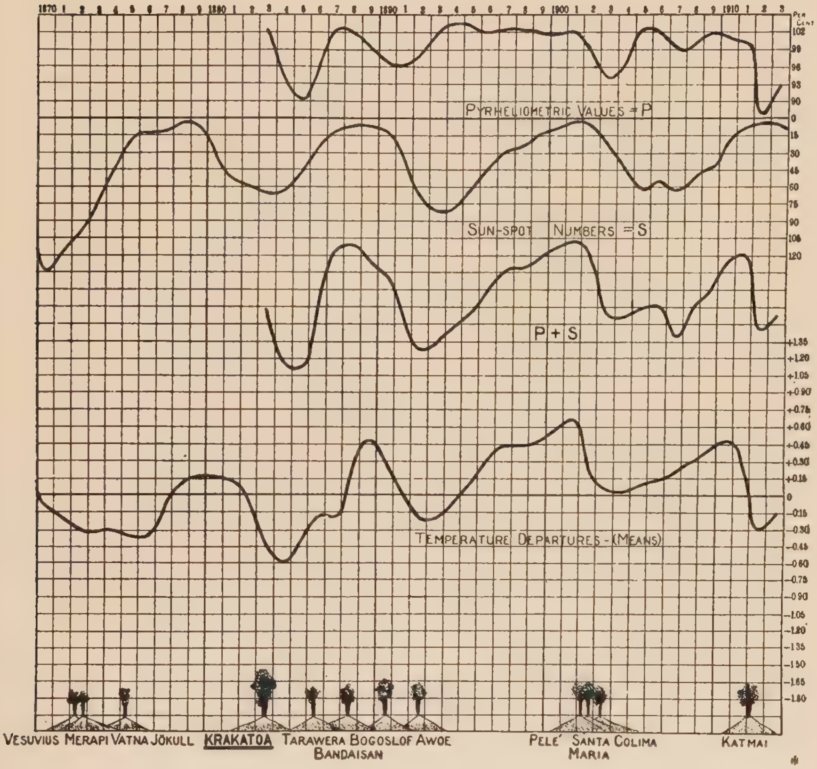

Fig. 1.

Pyrheliometric Values, Mean Temperature Departures, Sunspot Numbers, and Violent Volcanic Eruptions, from 1870 to 1913.

(*After Humphreys.*)

Nevertheless, even in the eighteenth century the curves of sunspots and temperature show so much relationship that there seems good ground for believing that Humphreys is right in saying that "at least since 1750 . . . and presumably, therefore, since an indefinitely distant time in the past, the two phenomena, atmospheric temperature and sunspot numbers, have in general varied together, with, however, marked discrepancies from time to time."[16]

In many instances these discrepancies occur immediately after violent volcanic eruptions of the explosive type which fill the upper air with dust all over the world. The amount of heat thus shut off from the earth may be approximately measured by the delicate instrument known as the pyrheliometer, as shown by the upper line in Fig. 1. Thus the sunspot curve needs to be modified to make allowance for the amount of solar radiation excluded from the earth's surface by volcanic dust. When this is done (P+S, Fig. 1), the agreement between terrestrial temperature and its supposed causes becomes more marked than when solar conditions alone (S, Fig. 1) are used. This furnishes an excellent illustration of the way in which terrestrial and solar causes of the most diverse types may coöperate to produce a single result. Nevertheless, for the half century for which sufficient data are available, it appears that when the effect of the seasons and of short fluctuations is eliminated, as in Fig. 1, at least four-fifths of the earth's variations in temperature have been due to changes in the sun.

Other studies lead to a similar conclusion. To take a single example, Arctowski,[17] in a careful analysis of monthly temperatures, brings out this point very clearly. By using the departure from the normal seasonal temperature at Arequipa in Peru and at many other stations, he demonstrates that the earth normally passes through temperature cycles having a length of two or three years. These in turn are superposed upon larger cycles having the eleven- or twelve-year sunspot period, and these on still larger cycles. Occasionally the cycles are interrupted by volcanic eruptions, but these, as we have seen, explain only a minor part of the variations. The similarity of Arctowski's curves in widely separated parts of the world seems to confirm a vast body of other evidence in indicating that cycles of temperature upon the earth are due largely to some outside cause.

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[16] *Loc. cit.*, p. 598.

[17] H. Arctowski: The Solar Constant and the Variations of Atmospheric Temperature at Arequipa and some other Stations, Bull. American Geographical Society, Vol. 44, 1912, pp. 598-606. Also, A Study of the Change in the Distribution of Temperature in Europe and North America during the years 1900 to 1909, Annals N. Y. Acad. of Science, Vol. 24, 1914, pp. 39-113.

CHAPTER II

THE SUN'S EFFECT ON STORMINESS[1]

HAVING seen that many of the earth's variations in temperature appear to be closely connected with solar changes, let us consider cyclonic storms. The chief storms are of two types—tropical hurricanes, and the ordinary cyclonic storms of temperate latitudes. Tropical hurricanes have been investigated in the Atlantic Ocean by Pöey,[2] and in the Indian Ocean by Meldrum.[2] These authors conclude that the hurricanes vary in number and intensity in harmony with sunspots. Wolf[2] has compared the hurricanes with the sunspot numbers

TABLE 1

TROPICAL HURRICANES AND SUNSPOTS BY YEARS

Number of hurricanes per year	*Relative sunspot numbers*
1 and 2	17
3	59
4	62
5	70
6 and 7	80
8	88

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[1] Much of this chapter is based on The Solar Hypothesis of Climatic Changes, Bull. Geol. Soc. Am., Vol. 25, 1914, pp. 477-590.

[2] These writers are quoted by J. Hann in his Klimatologie, Vol. 1.

and gets the interesting result shown in Table 1. This seems to show an unmistakable relationship.

In order to test the matter more fully I have made a new investigation, using the month instead of the year as the unit, and employing all available records of hurricanes from 1800 onward for over a century.[3] The results confirm Table 1, but add certain interesting details. Table 2 shows how the hurricanes of the world as a whole vary from season to season under different conditions of solar activity. During the spring, which means April to June north of the equator and October to December to the south, there is a pronounced gradation from 2.69 hurricanes per month, when the sunspot numbers are below 40, to 4.55 when the sunspot numbers are above 80. In summer and autumn a similar condition prevails, the ranges being in summer from 5.88 hurricanes per month with few sunspots to 6.99 with many, and in autumn from 2.20 to 3.12. In winter, on the other hand, the number of hurricanes is 40 per cent less with many sunspots than with few. Nevertheless, the number of tropical hurricanes is so small in winter—only about 5 per cent as great as in summer—that for the year as a whole the hurricanes during and immediately after months having sunspot numbers above 80 are 34 per cent more numerous than during and after months having sunspot numbers less than 40. This seems to be fairly conclusive evidence that earlier investigators have been right in concluding that sunspots and the type of atmospheric turbulence known as tropical hurricanes are somehow connected, and that increased solar activity means increased terrestrial activity.

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[3] Since this investigation was completed, S. S. Visher, Mo. Weath. Rev., Vol. 50, 1922, No. 6, pp. 288-297; No. 11, pp. 583-589, has published a new list of tropical cyclones and typhoons in Pacific regions, which is much fuller than any previous list.

W. E. Hurd, in the Pilot Chart of the Central American Waters, April, 1923, U. S. Weather Bureau, has also begun a list of "Tropical Storms of the Eastern North Pacific Ocean."

TABLE 2

SUNSPOTS AND TROPICAL HURRICANES BY SEASONS[4]

(A=number of months. B=average number of hurricanes.)

Sunspot numbers		*Spring*		*Summer*		*Autumn*		*Winter*		*Year*	
		A	*B*	*A*	*B*	*A*	*B*	*A*	*B*	*A*	*B*
I.	0-40	188	2.69	188	5.88	188	2.20	187	0.35	752	2.78
II.	41-80	100	2.96	101	6.35	104	2.61	99	0.32	404	3.08
III.	Over 80	48	4.55	47	6.99	49	3.12	50	0.21	194	3.72
Excess of III over I		69%		19%		42%		—40%		34%	

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[4] This table is based on the data given in the publications noted below. It embraces all the regions from which tropical hurricanes are reported. Spring in this table and in Table 3 is the months of April to June in the northern hemisphere and October to December in the southern, etc. The figures in the table show the average number of tropical hurricanes per month in the months having a given degree of solar spottedness and in the succeeding month. This method is used because there must be an appreciable lag from the time of a given solar condition until its supposed effect appears in a full-fledged hurricane.

E. B. Garriott: West Indian Hurricanes, U. S. Weather Bureau, Bull. H, Washington, 1900.

Oliver L. Fassig: Hurricanes of the West Indies, U. S. Weather Bureau, Bull. X, Washington, 1913.

José Algué: Cyclones of the Far East, U. S. Weather Bureau, Special Report, Philippine Weather Bureau, Manila, 1904.

A. Schück: Beiträge zur Meereskunde, III Fortsetzung zur Kenntnis der Wirbelstürme, Hamburg, 1906.

After the preceding study was made Mrs. E. V. Newnham published a valuable study of Hurricanes and Tropical Revolving Storms, Meteorological Office, Geophysical Memoir, No. 19, London, 1922. Mrs. Newnham says: ''Meldrum detected a relation between the frequency of storms near Mauritius and the sunspot period, and this has received further support from more recent observations. The records from the West Indies, the China Sea, and the Bay of Bengal, however, show no relation to sunspots nor to one another.'' The fuller analysis given below in Table 3 shows that the Bay of Bengal should be omitted from her list of regions where the hurricanes show no positive solar relations, while the South Pacific Ocean should be added as a region showing negative relations.

The solar effect upon tropical hurricanes does not appear to be the same in all parts of the world. This is shown in Table 3. There the data of Table 2 are rearranged according to five geographical areas, the Arabian Sea being counted with the Bay of Bengal not only because of proximity, but because its tropical hurricanes are too rare to be of much significance when studied alone. From Table

TABLE 3

SUNSPOTS AND TROPICAL HURRICANES BY REGIONS

(A=number of months. B=average number of hurricanes per month.)

	Sunspot numbers	*Bay of Bengal and Arabian Sea 1800-1905*		*South Indian Ocean 1848-1905*		*North Pacific Ocean 1880-1901*		*West Indies 1800-1911*		*South Pacific Ocean 1830-1905*	
		A	*B*	*A*	*B*	*A*	*B*	*A*	*B*	*A*	*B*
Spring	I. 0-40	179	0.313	86	0.530	35	1.515	188	0.114	110	0.214
	II. Over 40	129	0.503	86	0.628	31	1.772	148	0.101	118	0.144
	Excess of II		0.190		0.098		0.257		—0.013		—0.070
	over I		61%		19%		17%		—11%		—33%
Summer	I. 0-40	178	0.414	86	0.721	33	3.482	188	0.732	110	0.422
	II. Over 40	140	0.501	88	1.352	33	3.533	148	0.713	118	0.305
	Excess of II		0.087		0.631		0.051		—0.019		—0.117
	over I		21%		88%		1%		—3%		—28%
Autumn	I. 0-40	178	0.278	88	0.250	39	1.641	188	0.231	108	0.023
	II. Over 40	140	0.290	86	0.378	28	1.750	148	0.240	120	0.013
	Excess of II		0.012		0.128		0.109		0.009		—0.010
	over I		4%		51%		7%		4%		—43%
Winter	I. 0-40	177	0.020	86	0.017	36	0.222	187	0.091	111	0.009
	II. Over 40	141	0.072	88	0.028	29	0.120	149	0.084	117	0.004
	Excess of II		0.552		0.011		—0.102		—0.007		—0.005
	over I		260%		65%		—46%		—8%		—56%

3 it appears that at all seasons in both the northern and southern parts of the Indian Ocean the number of hurricanes at times of great solar activity is greater than at times of slight activity. In the North Pacific Ocean, that is, in the East Indies region of typhoons, there is a similar but small excess of hurricanes at times of many sunspots, but this gives place to a deficiency in winter. In the West Indies, however, as appears from the minus signs in Table 3, storms at all seasons except the autumn are slightly less numerous with high solar activity than when sunspots are scanty. In the South Pacific Ocean this reversal of the conditions of the Indian Ocean is complete, and at all seasons hurricanes are significantly less numerous when sunspots are abundant than when they are few.

This apparent contradiction is directly in line with what is found on close analysis in practically all relations between the activity of the solar and terrestrial atmospheres. That is, certain areas are influenced in one way and others in the opposite way. This seems at first unreasonable, and has been counted by many authorities as evidence that the apparent relationships are not real. Nevertheless, the evidence of a relationship is so strongly cumulative, the regularity of the figures in Tables 2 and 3 is so great, and the total excess of hurricanes, 34 per cent, at times of abundant sunspots is so large that the reality of the relationship seems highly probable.

A partial explanation of the apparent increase of hurricanes in some regions and decrease in others may possibly be found in a study of where the hurricanes originate and what paths they follow. For example, Table 4 shows the average sunspot numbers for the months when the hurricanes shown in Fassig's charts of the West Indies originated in four successive zones from east to west. The 33 hurricanes which originated farthest east, and whose average origin, so far as recorded, was longitude 59°W., occurred in months whose average sunspot number was 39.0. The next two groups whose average points of origin were in longitudes 68° and 78°W. had sunspot numbers less than three-fourths as large as those during the months when the most easterly group originated. Farther west, and centering about longitude 88°W., there is again an area where many hurricanes originated at times of fairly high sunspot numbers. Whether there is any significance in this fact cannot yet be determined. We shall find later that in the United States, at times of many sunspots, storms increase on the margins of the country while decreasing in the interior. If similar conditions prevail in the North Atlantic, many hurricanes might originate far to the east at times of abundant sunspots, and might swing north without being recorded as of tropical origin because few ships sail that part of the ocean and the records are relatively scanty. Thus storms might possibly be more numerous than now appears at times of many sunspots. Although nothing is yet certain in this

TABLE 4

LONGITUDE OF ORIGIN OF WEST INDIAN HURRICANES COMPARED WITH SUNSPOTS

Average Longitude	*Number of Cases*	*Average Sunspot numbers*
59°W.	33	39.0
68°W.	32	28.5
78°W.	32	27.1
88°W.	32	40.0

respect, the place of origin of hurricanes under different solar conditions is well worth investigating. All that we can now say with certainty is that so far as records are available tropical hurricanes as a whole are especially numerous when the sun's atmosphere is greatly perturbed, but this is true chiefly in the typhoon regions bordering Asia and south of that continent, while it is actually reversed in the less important hurricane areas of the West Indies and South Pacific.

The cyclonic storms of temperate latitudes are far more numerous and important than the hurricanes and typhoons of low latitudes. These can best be studied in the United States, not only because they are numerous there, but because nowhere else has any such large area been systematically covered by homogeneous and scientific observations. From the monthly maps of storm tracks compiled by the United States Weather Bureau, Kullmer[5] has compiled data as to the number and paths of storms, that is, of centers of low pressure, from 1874 to 1918. He divided the United States and southern Canada into a series of rectangles measuring 2½° in latitude and 5° in longitude. He then counted the number of storm tracks passing through each rectangle during each month of the year. The total for the year gives the relative storminess as shown in Fig. 2, where the figures for the various squares are the average values for 30 years.[6] The map shows a pronounced bow-shaped area of great storminess

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[5] Charles J. Kullmer: a chapter in The Climatic Factor, Carnegie Institution of Washington, No. 192, 1914; also sections in The Solar Hypothesis of Climatic Changes, Bull. Geol. Soc. Am., Vol. 25, 1914; and an article in Proc. 2d Pan-American Sci. Cong., Vol. 2, pp. 338-393. This last contains a large series of maps.

[6] The marginal portions of this map possess by no means the same degree of reliability as the main portions. For example, the apparent decrease in storms around Hudson Bay is partly, but by no means wholly, due to the paucity of observations.

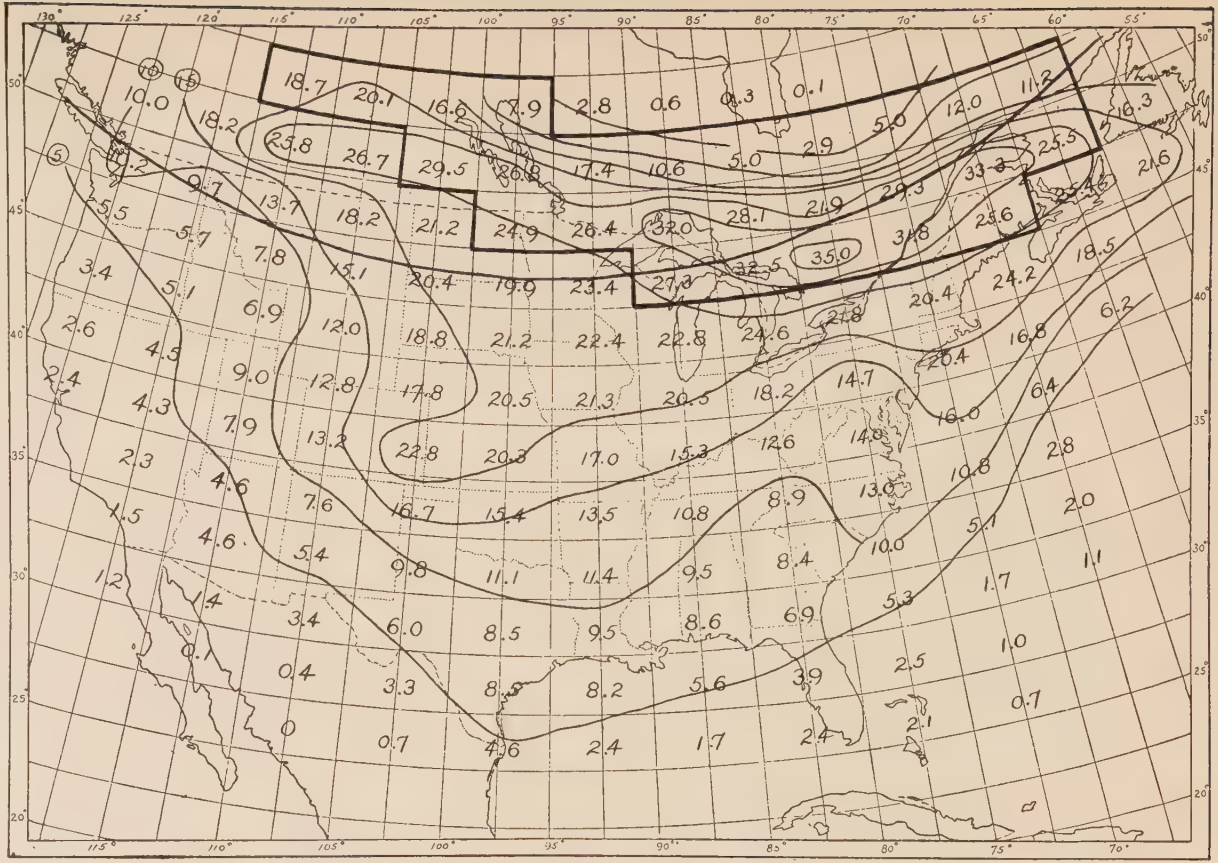

Fig. 2.

Storm Tracks in the United States.
(*After Kullmer.*)

Average number of storm centers crossing areas 2½° in latitude and 5° in longitude per year during the thirty years from 1883 to 1912.

swinging from British Columbia into the northern United States, across the Great Lakes and down the St. Lawrence Valley. A minor area of relatively high storminess is found in southeastern Colorado. The number of storms in one area as compared with another is not a measure of the amount of rainfall, since that is largely influenced by latitude, nearness to the ocean, the location of mountains, and other topographic considerations. Nevertheless, the variations in rainfall from year to year in any given locality are closely proportional to the number of storms, for the topographic conditions in any one place, of course, remain constant.[7]

TABLE 5.

STORMINESS OF 4-YEAR PERIODS IN NORTH AMERICA, EXPRESSED IN PER CENT OF AVERAGES FOR THE 30 YEARS, FROM 1883 TO 1912

Years	*Per cent of storminess*
1876-1879	89.5
1880-1883	79.0
1884-1887	90.0
1888-1891	99.9
1892-1895	110.1
1896-1899	103.0
1900-1903	100.5
1904-1907	105.7
1908-1911	98.6
1912-1915	109.5
1916-1918 (3 years)	123.2

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[7] In using Kullmer's data allowance must be made for the fact that the early figures are less reliable than those of later years. After about 1890 the data not only cover a wider area than at the beginning, but barometric minima of smaller dimensions have apparently been included. This is illustrated in Table 5, where the 43 years from 1876 to 1918 have been divided into 11 groups, all except the last containing four years. The average number of storms for the 30 years from 1883 to 1912 is called 100 per cent. For the first two groups of years allowance has been made for the fact that the data extend only as far west as the 100th meridian. Even so, these groups and

Let us inquire to what extent the actual amount of storminess varies in harmony with the number of sunspots. The matter may be investigated in various ways. First, let us take the three years of fewest sunspots in each sunspot cycle and compare them with the succeeding three years of maximum spots. This method is of especial interest, because these are the groups of years used by Kullmer in the highly significant maps which will be presented in a later chapter. Since storm records have been kept, there have been four complete sunspot cycles, all but the last of which have been of mild intensity compared with some of their predecessors. In these we have four

also the third group, 1884-1887, show a deficiency which is presumably due to the scarcity of early observations. Beginning with 1888, however, the figures seem to be fairly reliable, for the 99.9 per cent for the years 1888-1891 is practically the same as 100.5 for 1900-1903, and is larger than 98.6, the figure for 1908-1911.

After the publication of Kullmer's data in The Solar Hypothesis of Climatic Changes, 1914, some of Kullmer's results were criticized on the ground that the weather maps during the earlier years of the United States Weather Bureau were of necessity far less accurate than those of today. Professor A. J. Henry of the Weather Bureau, who has examined Kullmer's data with care and who has a most intimate knowledge of weather maps, puts the matter thus: "I do not question Professor Kullmer's methods. . . . My criticism was directed against using the data of storm tracks throughout the entire period (1883-1912) on the implied assumption that they are homogeneous. The record of storm paths beginning in 1891 is based on more complete data than for earlier years, and I consider the maps for that and later years as being much superior to those of former years. There is a personal equation in drawing maps of storm paths that cannot be eliminated . . . and therein lies one of the objections to basing a conclusion upon the number and frequency of plotted storm paths. The intense, the moderate, and the weak storms are all bunched together, and there is no means of disentangling the real from the apparent. Still, since there are no other data bearing upon cyclonic frequency easily available, I do not urge disregarding them entirely. My counsel would be to use them with discretion and throw out of consideration the region west of say the hundredth meridian except along the border states."

When this book was nearing completion Professor Kullmer worked up the data for the years 1913 to 1918. The extraordinary way in which the strong sunspot maximum in 1917 confirms previous results seems to establish the general reliability of Kullmer's conclusion that variations in storminess are intimately correlated with the sunspot cycle.

periods of minima and four of maxima. A comparison of the first two periods—the minimum of 1877-1879 with the maximum of 1882-1884—is of little value, since the records of these early years are not reliable, and since for the minimum period the storm data extend only to longitude 100°W. Coming to the next two periods—the minimum of 1888-1890 compared with the maximum of 1892-1894—we find that during the sunspot maximum the storminess of the area covered by Fig. 2 was greater than during the minimum by 14.3 per cent of the mean for 30 years. As a measure of storminess we use the sum of the figures in all the squares in Kullmer's map for any given year. The storminess of the succeeding sunspot maximum, 1905-1907, exceeded that of its preceding minimum, 1900-1902, by 1.4 per cent, while during the great maximum of 1916-1918 the amount of storminess exceeded that of the minimum of 1912-1914 by no less than 21.0 per cent.

Let us next compare the complete sunspot cycle from 1889 to 1900, inclusive, with the succeeding one from 1901 to 1911. Each of these begins with a sunspot minimum and lasts until the year preceding the next minimum. The average sunspot number for the twelve years of the first

TABLE 6 A

SUNSPOTS AND STORMINESS IN NORTH AMERICA, 1889-1918

Average sunspot number for ten years	*Percentage of storminess in North America compared with average for 1889-1918*
6 (1.4 to 12.1)	96.2
36 (13.6 to 48.5)	96.3
72 (53.8 to 103.9)	106.0

TABLE 6 B

SUNSPOTS AND STORMINESS IN THE CHIEF STORM BELT OF NORTH AMERICA, 1883-1912

	Storminess in per cent of average
8 years with sunspot numbers below 10 (average 5.7) . .	85.4
7 years with sunspot numbers from 10 to 35 (average 21.1) .	99.3
8 years with sunspot numbers from 35 to 60 (average 46.8) .	101.6
7 years with sunspot numbers above 60 (average 70.4) . .	114.1

cycle was 38.8 and its storminess was 107.4 per cent of the average storminess for 30 years. The average sunspot number for the 11 years of the second cycle was 33.3 and its storminess was 99.8 per cent. Here, just as in the other case, storms were abundant when sunspots were abundant.

Table 6 A illustrates still another method by which we may compare the number of storms with the sunspot numbers. The 30 years for which the fullest records are available (1889-1918) have been divided into three equal groups according to the sunspot numbers. The increase in storminess when spots are abundant agrees with our results for tropical hurricanes. With cyclonic storms, as with hurricanes, however, all regions do not act alike. For example, in the North American area combining greatest storminess and greatest change, and enclosed within heavy meridians and parallels in Fig. 2, the increase in storminess at times of many sunspots is even more marked than for the whole country, as appears from an early investigation made in 1914. This is shown in Table 6 B, where the 30 years from 1883 to 1912, inclusive, have been divided into four groups of seven or eight years each

in accordance with the number of sunspots, just as was done for the whole country in Table 6 A. The inclusion of later years would increase this contrast. In view of this table and those for tropical hurricanes, it seems difficult to avoid the conclusion that a similar solar relationship is repeated on both the northern and southern borders of the region where cyclonic storms prevail.

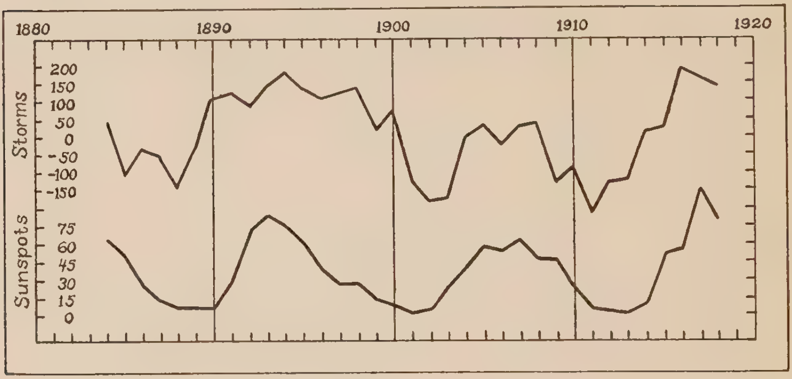

Fig. 3.

Sunspots (lower line) and Number of Storms in Main Storm Area of Southern Canada and the Northern United States (upper line).

Before leaving this subject, let us compare the number of storms in the main area of storminess with the sunspot numbers year by year.[8] If the years previous to 1883 were included in Fig. 3, it would be seen that for the seven years from 1874 to 1880, inclusive, the upper curve showing storms agrees closely with the lower one showing sunspots. Even the little maximum of 1877 appears in both curves. In 1881, however, the amount of storminess drops suddenly, although the number of sunspots keeps on increasing. This may be due partly to changes in the method of plotting the storm tracks on the Weather Bureau maps. Then for four years the two curves again agree, for both approach a maximum in 1884 and begin to fall in 1885. The next year the storms again behave differently from the sunspots, but this does not continue long, for in 1887 and 1888 both curves again decline. In 1891 both rise, but the following year shows disagreement. Thereafter a high degree of agreement is observed. It pertains not only to the major fluctuations, but to such little variations as the minor maxima of 1898 and 1900, both of which appear as irregularities in the sunspot curve. In the sunspot cycles between 1900 and 1910 each of the three irregularities in the upper curve is apparent in the lower, while in the last cycle both sunspots and storms rise higher than before.

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[8] In Fig. 3, as well as in the correlation coefficients discussed below, I have omitted the early years from 1874 to 1882 when the data covered only part of the country. The reason is that even when allowance is made for the omitted parts of the country the results for these years are uncertain. Nevertheless, they agree on the whole with the sunspot curve. Helland-Hansen and Nansen, in discussing this curve as given in The Solar Hypothesis, point out that I have underestimated the solar relationship because I have not considered periods shorter than the eleven-year sunspot cycle, nor have I compared the storms with disturbances of the magnetic elements, which are generally agreed to be of solar origin.

The relationship shown in the two main curves of Fig. 3 forms, so to speak, a concrete summary of the relation between the sun and the weather, and should be tested rigorously. One of the most severe mathematical tests is correlation coefficients. It will be remembered that in computing these it is first necessary to find the amounts by which each entry in the tables representing the variations of two phenomena departs from the average for its entire series. From these values the standard mathematical method of Pearson makes it possible to determine the exact degree of relationship.[9] If the two phenomena are absolutely unconnected the coefficient is zero. If they are absolutely connected so that one never occurs without the other, and the relationship can be expressed by an invariable and simple mathematical formula which can be plotted as a straight line, the coefficient is 1. Such a relationship is like that of the rising of the sun to the rotation of the earth, or of the driving wheels of an engine to the stroke of the piston. A less intimate but still close relationship, such as that between the amount of food which a horse eats and the amount of work that he does, is expressed by a coefficient which cannot possibly rise as high as 1, or fall as low as zero. The coefficients may have either a plus or a minus sign. The sign is positive when the maxima of one phenomenon are connected with the maxima of the other, while it is negative

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[9] Throughout this book the correlation coefficients (r) are computed by the formula $r = \frac{\Sigma A \times B}{\sqrt{\Sigma A^2 \times \Sigma B^2}}$, and the probable error (e) by $e = \frac{1 - r^2}{\sqrt{n}} 0.674$.

TABLE 7

PROBABILITY OF OCCURRENCE OF CORRELATION COEFFICIENTS OF DIFFERENT MAGNITUDES RELATIVE TO THE PROBABLE ERROR[10]

Ratio between correlation coefficient and probable error	*Odds against the occurrence of a ratio as great as or greater than the one here designated*
1	1 to 1
2	5 to 1
3	22 to 1
4	142 to 1
5	1,350 to 1
6	19,230 to 1
7	434,782 to 1
8	1,470,588,234 to 1

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[10] Raymond Pearl and John Rice Miner: A Table for Estimating the Probable Significance of Statistical Constants, Maine Agricultural Experiment Station, Thirtieth Annual Report, 1914, p. 88.

TABLE 8

CORRELATION COEFFICIENTS BETWEEN YEARLY STORMINESS IN THE MAIN STORM TRACK AREA AND YEARLY SUNSPOT NUMBERS, 1889-1918

Sunspot year	*r* *Correlation coefficient*	*e* *Probable error*	*r/e* *Ratio of correlation coefficient to probable error*
3 years before storms	—0.036	±0.114	0.3
2 years before storms	+0.256	±0.106	2.4
1 year before storms	+0.505	±0.086	5.9
Same year as storms	+0.611	±0.071	8.6
1 year after storms	+0.591	±0.074	8.0
2 years after storms	+0.329	±0.102	3.2
3 years after storms	+0.003	±0.114	0.01

if the maxima of one are connected with the minima of the other. When the correlation coefficient is four times the probable error, the probability of a relationship is considered as almost established. What this really means, however, is that there is only one chance in 142 that two phenomena would accidentally vary together to the degree actually found. Table 7 shows the corresponding odds against an accidental agreement in the fluctuations of two phenomena when the ratio between the correlation coefficient and the probable error has other values.

Using this method we find that the correlation coefficient between the yearly sunspot numbers and the storminess in the whole of North America so far as data are available from 1889 to 1918 amounts to +0.47, which is 4.9 times the probable error. This means that there is only one chance in 1052 that the apparent connection between the two phenomena is the result of accident. It of course indicates nothing as to the nature of the relationship or as to whether it is direct or indirect. Nor does it show whether the relation is causal or whether both phenomena merely depend upon some other common factor or factors. It merely indicates that the odds are strongly against an accidental similarity in the fluctuations of the two phenomena.

In the case of the two curves of Fig. 3, the correlation coefficients between storms and sunspot numbers from 1884 to 1918 are shown in Table 8. In the first line the storms of a given year have been compared with sunspots three years before. The coefficient —0.036 is too small to be significant, less, indeed, than the probable error. It indicates that there is no relation between the storms, say of 1914, and the sunspots three years before, during 1911. The next line shows that when the storms are compared with the sunspots of two years before,—that is, when the storms of 1914, for example, are compared with the sunspots of 1912—there is a hint of a connection, but the coefficient is only twice the probable error. The next three lines show coefficients of +0.505, +0.611, and +0.591. Since these are from six to eight times the probable error they indicate a high correlation. The fact that the coefficients are so large and are arranged regularly and reach a maximum when the spots of a given year are compared with the storms of the same year is almost conclusive evidence that the amount of storminess in the United States is really dependent upon variations in the sun's atmosphere, or else that the two are due to some common cause whose nature is not yet known. The possibility that we are here being accidentally misled amounts to only one chance in billions.

In Europe the records of storms have been so imperfectly charted that they are of little use for our present purpose. So far as they go, they agree with those of the United States in indicating a solar relationship.[11] Moreover, Douglass[12] has made an important study of the relation of tree growth to the weather in Europe, and this enables us indirectly to obtain some light on the relation between storms and sunspots for a hundred years. He has shown that the annual rings of growth in trees form a fairly reliable index of climate. In dry climates, or at least on dry slopes in such climates, the width of the rings is primarily a measure of the amount of rainfall, while in moister climates and in swampy places other factors, such as temperature, sunshine, and the length of the growing season, may play the most important parts. The delicacy of Professor Douglass' methods is so great that by means of the relative thickness and character of neighboring rings he can in some species identify the year of growth of any part of the tree trunk provided he can compare it with wood of the same date belonging to trees of the same species whose date of cutting is known, and which grew in the same region. In Germany, at Eberswalde, near Berlin, he has made some measurements which afford one of many examples of correlations that are important in the present connection. The results are shown in Fig. 4. The lower curve is that of sunspots. The curve above it shows the growth of thirteen pine trees.[13] The extent to

[11] Ellsworth Huntington: The Solar Hypothesis of Climatic Changes, Bull. Geol. Soc. Am., Vol. 25, 1914, pp. 477-590.

[12] A. E. Douglass: Climatic Cycles and Tree Growth, Carnegie Institution of Washington, Publication No. 289, 1919. The Climatic Factor, No. 192, 1914, Chapter XI. See also article in Ecology, Vol. 1, 1920.

[13] This has been smoothed by the formula $\frac{a+2b+c}{4}=b$ to eliminate minor vagaries, but not in such a way as to influence the main sinuosities. It has also been corrected in order to eliminate the effect of the more rapid growth of trees in youth than in maturity and old age. These processes are discussed in full in The Climatic Factor (Pub. No. 192 of the Carnegie Institution of Washington). It will there be seen that the personal opinion of the investigator does not materially influence the results.

which the two main curves agree is remarkable. With one exception the seven maxima of the sunspot curve are faithfully reproduced in the tree curve. The minima agree equally well. The only exception begins in 1892 and continues until 1899. It may be due to some meteorological condition or to some such thing as insect pests. If the growth of the trees had not been checked, their curve would probably have agreed closely with that of the sunspots. This conclusion is strengthened by the fact that in 1900 we have a little minimum corresponding to the minimum in the sunspot curve, but occurring slightly before it, as is usually the case.

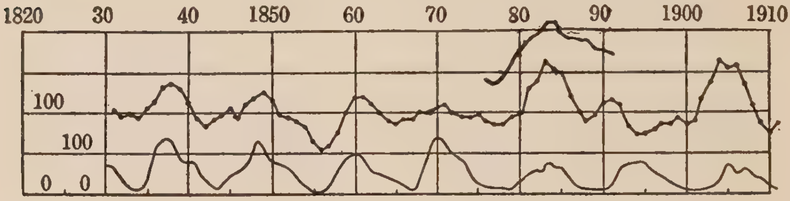

Fig. 4.

Growth of Trees at Eberswalde, Germany, compared with Sunspots and Summer Storms.

(*After Douglass.*)

Upper curve=summer storms (April-November).
Middle curve=growth of pine trees.
Lower curve=sunspots.

In order to determine exactly what climatic conditions are indicated by the tree curve of Fig. 4, I have worked out two sets of correlation coefficients for each month of the year, one set being the relation between temperature and tree growth and the other between rainfall and tree growth. A period of 50 years, 1851 to 1900, was used for rainfall, and 42 years, 1866 to 1907, for temperature, these periods being determined by the records which happened to be available. The coefficients show that rapid growth is correlated chiefly with two conditions. The first is relatively high temperature in the late winter and early spring; the second, abundant rainfall from April to November. The amount of snow in the winter appears to be of comparatively little importance except where it prevents the air from growing warm in the spring. The departure of the summer temperature from the normal also makes relatively little difference. These facts suggest that the most favorable conditions for the growth of trees in Germany are periods when rainfall is abundant during the summer and when the winters are comparatively free from storms and snow, so that the trees can begin their growth early in the season. The amount of rainfall in climates like that of northern Germany depends largely on the number of cyclonic storms. In order to illustrate the relation of storms to the growth of the trees, I have added to Fig. 4 a little upper curve showing the number of storms from April to November, inclusive, during the period from 1876 to 1891, the only period during which such data are available. The figures for this smoothed curve have been kindly supplied by Professor Kullmer. They include all the storms whose centers passed within 2½° north or south of Eberswalde. The earlier portion of the curve probably falls too low; for, as Professor Kullmer points out, the records of storms in Europe during the early years of the present series are not particularly reliable. Nevertheless, the curve thus obtained agrees in its main features with the curve of the trees. The agreement is not perfect, however, for other factors, such as the temperature of the early spring, play a part in determining the rate of growth. The evidence of the curve, together with what has just been said as to the conditions most favorable to tree growth, probably justifies us in concluding that the curve of tree growth shown in Fig. 4 represents the main fluctuations in the cyclonic storms of central Europe in summer.

The curve of tree growth represents not only the number of summer storms, but also the conditions of the winter, as has already been said. Where the curve is high the months of February and March appear to have been fairly dry. It will be noticed that these conditions—that is, abundant storms and rain in summer and little snow in winter so that the air can become warm early in the spring—are typical of continental climates. In oceanic climates, although the winters are on the whole warm and wet, the springs are relatively cool and the summers are not apt to show markedly more precipitation than the winters. In view of this, then, we may interpret the curves of Fig. 4 as meaning that when sunspots are numerous, continental conditions of climate prevail in northern Germany. This carries with it the implication that at such times the continental areas of high pressure tend to become intensified in winter, so that the air blows outward from them and cyclonic storms are compelled to move along the margins of the continent rather than toward the interior. In summer, on the contrary, the low pressure area of the center of Eurasia appears to become intensified, and this causes the winds to blow toward the interior and to bring abundant moisture. The full importance of this is shown in *Climatic Changes,* where the climate of the past is discussed. The point to be emphasized here is that so far as we are yet able to secure data, the storminess of central Europe during the summer appears to vary in close harmony with variations in sunspots.

The conditions in Europe must be considered in connection with those in other parts of the world. On the basis of the records of a century we have seen that tropical hurricanes, taken as a whole, vary in number in fairly close harmony with sunspots. The cyclonic storms of the United States, if we may judge from a period of forty years, vary in the same way. The storms of Europe likewise show indications of similar variations, although the record is too short and imperfect to be of much value. The indirect evidence of trees, however, gives a period of about a century for which data are available in central Europe, and the agreement between sunspots and storminess appears to have been strongly marked throughout practically the whole time. Nowhere else are records of cyclonic storms available on a sufficient scale to be of much use in the present investigation. Thus we conclude that so far as evidence is yet at hand, it suggests that the degree of storminess upon the earth varies in fairly close harmony with disturbances of the sun's atmosphere as indicated by sunspots. Nevertheless, certain areas show the opposite type of relationship, a conclusion which will be discussed more fully in Chapter V.

CHAPTER III

SOLAR REGULATION OF ATMOSPHERIC PRESSURE[1]

NOT only do temperature and storminess appear to be connected with sunspots, but there is evidence that solar activity influences atmospheric pressure. Many investigators have worked on this problem, and their results are summed up by Helland-Hansen and Nansen.[2] Walker[3] has gone so far as to publish a map showing to what extent variations in pressure in all parts of the world harmonize with variations in sunspots. Helland-Hansen and Nansen,[2] Brooks,[4] and Okada,[5] carry the matter into greater detail. They make it practically certain that Bigelow, the Lockyers, Hildebrandsson,[6] and Arctowski[7] have been on the right track in this matter.

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[1] This chapter is based on an article entitled Solar Disturbances and Terrestrial Weather, Mo. Weath. Rev., March, April, and June, 1918, 46: 123-141, 168-177, 269-277.

[2] B. Helland-Hansen and F. Nansen: Temperaturschwankungen des Nord-Atlantischen Ozeans und in der Atmosphäre, 1917. (See Note 11, Chap. I.)

[3] G. T. Walker: Correlation in Seasonal Variations in Weather, VI. Sunspots and Pressure, Mem. Ind. Meteor. Dept., Vol. 21, Pt. 12, 1915.

[4] C. F. Brooks: Ocean Temperatures in Long-range Forecasting, Mo. Weath. Rev., Vol. 46, 1919, pp. 510-512.

[5] T. Okada: Mo. Weath. Rev., Vol. 44, 1916, pp. 17-21, 238-240; Vol. 45, 1917, pp. 299-300, 535-539.

[6] H. Hildebrandsson: Quelques recherches sur les centres d'action de l'atmosphere, Kongl. Svenska Vetenskaps-Akademiens Hardlingar, Vol. 29, No. 3, 1897; Vol. 32, No. 4, 1899; Vol. 45, No. 2, 1909; Vol. 45, No. 11, 1910; Vol. 51, No. 8, 1914.

[7] H. Arctowski: About Climatical Variations, Am. Journ. Sci., Vol. 37, 1914, pp. 305-315. See also earlier references to this prolific and suggestive writer.

Centers of barometric action are scattered here and there over the earth's surface. They fall into two distinct groups. In general, high pressure areas form one group. They are characterized by rising pressure at times when the other group, composed of centers of low pressure, shows a decrease. Likewise the two groups show simultaneous changes of temperature, but in opposite directions. In intermediate regions somewhat irregular variations occur, but in many cases these are similar to those of a neighboring center of action, but with a delay of some weeks or months. The simultaneous character of the variations in widely separated areas and their evident unity of action and of periodicity strongly suggest that they are initiated by some outside cause. The synchronism of their periods with those of various solar phenomena, such as sunspots, prominences, and magnetic action, makes it almost certain that this outside cause is the sun. According to the full and clear discussion of Helland-Hansen and Nansen in their study of the North Atlantic, it seems not improbable that in many cases a change in solar activity gives rise first to a change in atmospheric pressure, then the winds change, and finally the temperature is affected by the winds.

In order more fully to test the relation of the sun to barometric pressure I have made a study of barometric gradients. So far as the weather is concerned, the most important fact is not so much whether the barometric pressure is high or low, but whether the pressure differs much or little from that which prevails a few hundred or a thousand miles away. In other words, the important factor is the gradient. On this, in general, depend the force of the winds, the violence of storms, and the changes in temperature and humidity. Steep gradients are generally accompanied by low pressure and stormy weather, while gentle gradients are, as a rule, accompanied by high pressure and fair weather. In order to compare the gradients with sunspots, I have used the daily barometric maps of the North Atlantic Ocean prepared by the Deutsche Seewarte for the ten years 1904-1913. The maps cover the North Atlantic and the neighboring continents as far as Lake Superior, Hudson Bay, and northern Labrador on the west, and the central Baltic and southern France on the east. In order to find the average gradient a count was made of the intersections of the isobars with the degree net formed by every fifth meridian and every fifth parallel of latitude. The numbers thus obtained may be called the ''gradient index.'' These index figures show a relationship to solar disturbances. When the sun's atmosphere is particularly active, and especially when the acitvity is great upon the margins of the sun's visible disk, the North Atlantic Ocean and the neighboring lands usually have steep gradients and hence are subject to strong changes of weather. The appearance of a pronounced disturbance on the margin of the sun's disk is usually followed by a severe storm, after which comes a period of exceptionally calm clear weather. The details on which this conclusion is based are given in the rest of this chapter.

The significance of the gradient index may be estimated by measuring the length of the parallels and meridians and dividing that length by the number of intersections. If the total length of the parallels and meridians should be 40,000 miles and the index, or number of intersections, 100, the isobars would be separated by an average interval of approximately 400 miles. A gradient index of 50 would mean an average interval of about 800 miles. For practical purposes such a reduction to miles is not necessary. The index figures may be used directly as obtained by counting. A high figure means a steep gradient, and in general points to stormy conditions and high winds.

Although this method of computing the gradients answers our present purpose, it is open to certain objections. It gives a genuine measure of atmospheric activity, but does not indicate exactly the intensity of air flow. What is needed is some means of measuring "turbulence," that is, both the intensity and area of atmospheric movements, but as yet no such means has been devised. In addition to this general defect pertaining to the whole science of meteorology, there are minor objections pertaining to this particular method. For instance, an isobar may waver back and forth so that it crosses the same parallel repeatedly. To balance this, however, other isobars repeatedly approach the lines of the degree net, but do not cross them. Actual study of the maps shows that neither of these conditions introduces any appreciable error. The isobars that avoid the parallels are obliged to cross the meridians with greater frequency, and vice versa. Moreover, in an area so large as that included in the maps of the Atlantic Ocean—more than 12,000,000 square miles—the isobars are sure to run in all directions. When several days are averaged together, any possible error from this source becomes negligible.

A more important objection arises from the fact that the meridians converge northward. Suppose two storms with identical barometric gradients should center in latitudes 43° and 57° respectively. The number of intersections would be in the ratio of 130 to 155, a difference of 16 per cent. In future investigations it will undoubtedly be better to use a net formed of equidistant lines instead of the degree net. This was not done in the present case simply because it was impossible to undertake so much extra work. Fortunately the use of the simpler method does not alter our results except to make them less distinct. For our present purpose the most important consideration is the change in gradients from one day to the next. This averages between 16 and 17 per cent of the total gradient, and may rise as high as 80 per cent. The daily movement of the average storm toward the north or south, however, is usually only 2° or 3° and rarely exceeds 5°. In so short a distance the change in gradients due to the convergence of the meridians amounts to less than one-fifth of the average change due to other causes. It may mask the other changes somewhat, but cannot conceal them. In the southern section of the North Atlantic the effect is less than in the northern, for the meridians converge less rapidly. The parallels, of course, remain equally distant in all parts of the map, and hence introduce no error in the number of intersections.

Under certain circumstances other minor sources of error may affect the index figures for barometric gradients. They are discussed in the paper referred to at the beginning of this chapter, but are not sufficient to affect the results here given.

Although the method here employed is capable of considerable improvement, it appears to be the best yet devised for showing the general degree of barometric disturbance over a wide area. Within a week's time the gradients frequently swing from 30 or 40 per cent below the normal to an equal distance above it. If all the possible errors should reach a maximum at the same time, and should all produce an apparent swing in one direction, they could not cause a difference half as great as this. As a matter of fact, the various kinds of errors almost never reach a maximum at the same time, or combine in one direction. On the contrary, their constant tendency is to neutralize one another. This is especially the case where large numbers of days are averaged together. This point deserves emphasis. The very fact that our figures for barometric gradients are less exact than for the areas of sunspots makes it doubly significant that we find such strong evidences of a relationship. The errors in the index figures for gradients are not related to solar changes, for they are due to purely terrestrial and human causes. Therefore they fall indiscriminately at any phase of solar activity, and tend to conceal whatever relation may exist between changes in the weather and changes in the sun.

In making comparisons of weather and sunspots on the basis of the day instead of the month or year, as is usually done, it is necessary to go to the tables of daily measurements of solar photographs published by the Greenwich Observatory. Most sunspots consist of two portions, a dark central umbra and a lighter penumbra. The umbral areas average about one-sixth as large as the whole areas.[8] Therefore, in order to work with smaller numbers, the umbral areas are used for the years 1904-1909, when sunspots were abundant, but for the years 1910-1913, when spots were few, the whole areas have been employed. When it is necessary to obtain the combined results for the two sets of years, the figures for whole areas are divided by 6. In all cases the areas have been corrected for the foreshortening which is inevitable in a photograph of a curved surface like that of the sun.

After the daily index figures for gradients had been obtained by the method described above, the approximate normal gradient for each day was calculated. These normals are more than 50 per cent greater in winter than in summer. In order to eliminate this seasonal effect the index figures have been reduced to percentages of the normal. Thus a severe summer storm appears as important as a severe winter storm provided its gradients rise in equal proportion above the normal. Having reduced the gradients to percentages, it was easy to select from each year the days having either the steepest or the gentlest gradients, approximately 50 of each for each of the four years 1904, 1906, 1908, and 1909.[9] As sunspot records for certain days are lacking, only 390 days could actually be used. The 390 days thus selected were then compared with the conditions of the sun on each of the days in question, and for six days previously and five days subsequently. The results of this comparison are given in Table 9, and are shown graphically in Fig. 5.

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[8] The ratios for the two years, 1907 and 1908, when sunspots were numerous, are 6.6 and 6.4. For years when sunspots were few they are: 1910, 5.3; 1911, 5.5; 1912, 5.3; 1913, 9.4. Average for these six years, 6.4.

For the present only the lines marked A and A′ in Table 9 and Fig. 5 need concern us. Line A represents the total area of sunspots on all parts of the sun's visible surface for six days before and five days after 194 days of unusually steep gradients, while A′ represents the same thing for 196 days of unusually gentle gradients. During the years in question the spottedness of the sun was evidently much greater when the gradients were steep than when they were gentle. The maximum difference amounts to over 40 per cent and comes two days before what appear to be the terrestrial responses.

The reverse of the preceding investigation, that is, a direct examination of the steepness of the gradients over the Atlantic on days when the sun has a given degree of spottedness, has never been made. This is because during the preceding investigation it was found that the position of the spots upon the sun's visible disk seems to be as important as their area, as appears from a comparison of

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[9] In the preliminary investigation here concerned the periods used were March to December, 1904; May to December, 1906, 1908, and 1909, a total of 1037 days. In the investigations described later, the entire 10 years, 1904-1913, were employed.

TABLE 9

TOTAL AREAS OF SOLAR UMBRÆ IN RELATION TO DAYS OF EXTREME BAROMETRIC GRADIENTS IN STORMY AREA OF NORTH ATLANTIC OCEAN, MARCH TO DECEMBER, 1904, AND MAY TO DECEMBER, 1906, 1908, AND 1909

A=Total area of all umbræ.
B=Total area of umbræ within 30° of sun's central meridian.
C=Total area of umbræ 30°-90° east of sun's central meridian.
D=Total area of umbræ 30°-90° west of sun's central meridian.
E=Total area of umbræ more than 30° from sun's central meridian.

I. UMBRÆ IN RELATION TO 194 DAYS OF STEEPEST GRADIENTS

	Day before steep gradient						*Days of steep gradients*	*Day after steep gradient*				
	6th	*5th*	*4th*	*3d*	*2d*	*1st*	*0*	*1st*	*2d*	*3d*	*4th*	*5th*
A . .	22,611	23,679	24,029	24,538	24,733	24,374	23,696	23,796	22,837	22,622	23,477	22,432
B . .	9,689	9,379	9,060	8,338	8,165	8,885	9,470	10,902	10,068	10,385	9,833	8,863
C . .	5,681	6,433	6,665	7,402	7,473	7,471	6,790	6,031	5,974	5,252	5,910	5,762
D . .	7,214	7,867	8,304	8,798	9,095	8,019	7,436	6,863	6,795	6,985	7,736	7,807
E . .	12,893	14,300	14,969	16,200	16,568	15,490	14,226	12,894	12,769	12,237	13,646	13,569

II. UMBRÆ IN RELATION TO 196 DAYS OF GENTLEST GRADIENTS

	Day before steep gradient						*Days of steep gradients*	*Day after steep gradient*				
	6th	*5th*	*4th*	*3d*	*2d*	*1st*	*0*	*1st*	*2d*	*3d*	*4th*	*5th*
A′ . .	18,832	19,275	17,560	17,219	17,228	17,207	17,749	17,205	17,629	17,648	17,908	16,979
B′ . .	5,914	5,542	5,433	5,887	6,863	7,408	7,531	7,197	6,676	6,813	6,758	6,218
C′ . .	4,839	5,359	4,847	5,123	4,887	4,965	5,318	4,783	4,772	4,749	4,721	4,840
D′ . .	8,079	8,374	7,280	6,209	5,478	4,834	4,900	5,225	6,181	6,122	6,429	5,911
E′ . .	12,918	13,733	12,127	11,332	10,365	9,799	10,218	10,008	10,953	10,871	11,150	10,751

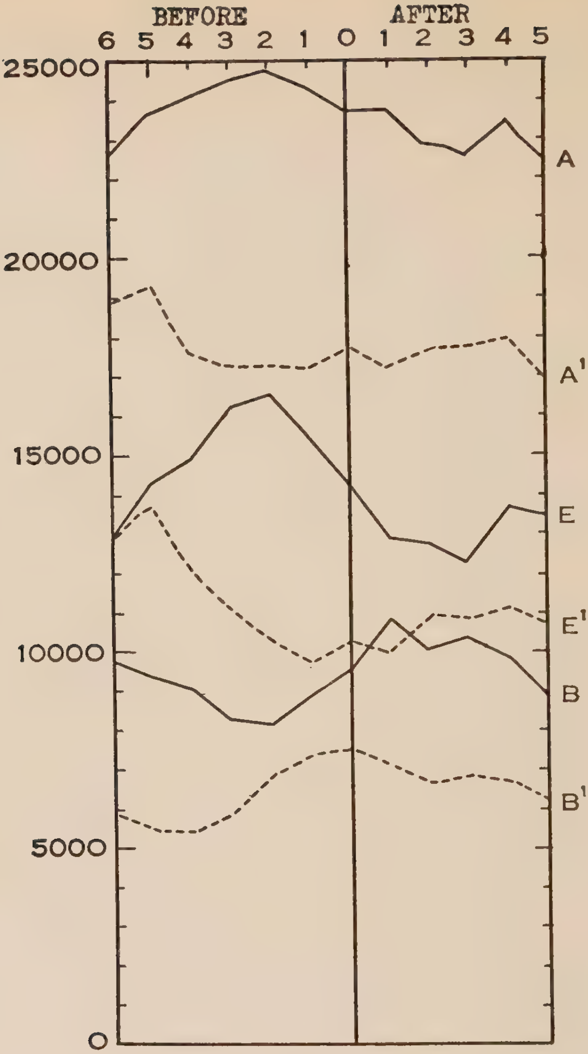

Fig. 5.

Total Areas of Solar Umbræ in Relation to Days of Extreme Barometric Gradients in the Stormy Area of the North Atlantic, 1904, 1906, 1908, 1909.

(*Courtesy of the United States Weather Bureau.*)

——————— areas accompanying steep gradients.
- - - - - - - areas accompanying gentle gradients.

For explanation see Table 9. This diagram deserves careful study in connection with the table. For example, line B shows the total area of the umbræ of sunspots within 30° of the sun's central meridian before and after days of high barometric gradients, and E the similar area of spots more than 30° from the central meridian. Two days before the occurrence of high gradients (their occurrence being on the day marked zero) line B falls to its minimum level while line E rises to a maximum. Lines B′ and E′ which pertain to days of gentle barometric gradients show an opposite relation. On or immediately before the days of gentle gradients line B′ for spots within 30° of the central meridian rises to a maximum, while line E′ for spots more than 30° from the sun's central meridian sinks to a minimum.

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CHANGES IN BAROMETRIC GRADIENTS OF ALL DAYS, MARCH, 1904, T

A, B, C, etc.=excess of sunspots within 60° of sun's margin in N. W. a

[N=Sum of changes of gradient in northern section of North America

Solar difference	*A, 0-10*			*B, 11-20*			*C, 21-30*			*D, 3*	
Year	*Days*	*N*	*S*	*Days*	*N*	*S*	*Days*	*N*	*S*	*Days*	*N*
1904 . . .	111	1,630	2,186	65	1,074	1,067	31	365	563	39	46
1905 . . .	82	1,275	1,288	36	524	754	35	545	577	49	74
1906 . . .	122	1,877	2,449	39	601	698	33	541	594	54	86
1907 . . .	80	1,366	1,550	51	819	853	36	587	600	35	57
1908 . . .	126	2,096	2,300	50	894	818	33	477	541	59	94
1909 . . .	132	2,136	2,065	43	643	925	38	573	699	37	63
Total . . .	653	10,380	11,838	284	4,555	5,115	206	3,088	3,574	273	4,21
Average . .		15.9	18.2		16.0	18.1		14.9	17.3		15

TA

CHANGES IN BAROMETRIC GRADIENTS OF ALL DAYS, MARCH, 1904, TO DECEMBER, 1 FOUR DAYS ENDING WITH THE DAY O

A, B, C, etc.=excess of sunspots within 60° of sun's margin in N. W. a

[N=for northern section of North Atlantic Ocean

Solar difference	*A, 0-5*			*B, 6-10*			*C, 11-17*			*D, 18-25*		
Year	*Days*	*N*	*S*	*Days*	*N*	*S*	*Days*	*N*	*S*	*Days*	*N*	
1904	43	607	709	36	525	671	50	776	971	52	851	
1905	11	128	135	17	228	296	22	294	479	37	512	
1906	39	502	809	25	388	531	48	783	1,119	32	486	
1907	11	250	139	23	431	459	33	404	506	27	380	
1908	39	671	732	35	625	666	54	905	1,005	33	409	
1909	35	581	534	36	587	551	43	749	790	43	586	
1910	129	2,092	2,393	34	582	729	36	637	491	47	734	1,
1911-1913	898	14,894	16,311	73	1,264	1,201	50	631	1,007	27	499	
Total for 1904-1913 . .	1,205	19,725	21,762	279	4,630	5,104	336	5,179	6,368	298	4,458	5,
Average for 1904-1913 .		16.4	18.1		16.6	18.3		15.4	19.0		15.0	

E 10

DECEMBER, 1909, COMPARED WITH SOLAR QUADRANT DIFFERENCES

S. E. quadrants compared with S. W. and N. E. quadrants, or vice versa.

S=Sum of changes of gradient in southern section of North Atlantic.]

50	*E, 51-75*			*F, 76-100*			*G, 101-150*			*H, over 150*		
S	*Days*	*N*	*S*	*Days*	*N*	*S*	*Days*	*N*	*S*	*Days*	*N*	*S*
612	28	440	530	16	173	268	10	213	197	6	117	70
882	49	841	963	32	518	819	37	632	635	44	888	900
964	50	726	825	29	560	508	26	525	455	12	167	171
572	54	954	937	27	318	590	29	491	410	53	1,183	1,171
1,200	43	774	768	22	313	288	18	303	308	15	192	190
761	34	612	612	30	337	782	25	300	598	26	411	427
4,991	258	4,347	4,635	156	2,219	3,255	145	2,464	2,603	156	2,958	2,929
18.3		16.8	18.0		14.2	20.8		17.0	18.0		18.9	18.8

E 11

3, COMPARED WITH AVERAGE SOLAR QUADRANT DIFFERENCES FOR THE PERIOD OF THE OBSERVED CHANGE OF GRADIENT

S. E. quadrants compared with S. W. and N. E. quadrants, or vice versa.

S=for southern section of North Atlantic Ocean.]

	E, 26-37			*F, 38-50*			*G, 51-75*			*H, 76-125*			*I, over 125*		
S	*Days*	*N*	*S*	*Days*	*N*	*S*	*Days*	*N*	*S*	*Days*	*N*	*S*	*Days*	*N*	*S*
0	45	653	897	28	355	518	30	411	609	17	266	251	5	134	136
0	53	985	943	50	802	863	56	935	1,263	62	1,020	1,152	56	997	1,121
6	61	786	1,059	44	729	759	61	1,093	1,087	46	918	767	8	112	136
8	51	853	836	36	660	567	68	1,029	1,506	60	995	1,105	57	1,307	1,153
7	62	1,019	1,083	38	521	682	69	1,475	1,170	21	305	328	15	199	126
3	51	647	1,101	36	639	626	52	861	1,182	39	555	878	30	479	532
9	43	524	776	27	450	474	32	534	588	14	192	193	5	58	90
5	31	532	564	9	76	152	6	44	73	1	16	18	0	0	0
8	407	5,999	7,259	268	4,232	4,641	374	6,382	7,478	260	4,267	4,692	171	3,228	3,294
.5		14.7	17.9		15.8	17.3		17.1	20.0		16.4	18.0		18.9	19.2

lines B and E, or B′ and E′ in Table 9 and Fig. 5. Indirectly, however, we can arrive at essentially the same result. Tables 10 and 11 show the degree of change in the barometric gradients from day to day compared with the differences between the spottedness of different parts of the sun's margin.[10] When such differences are great, the area of sunspots is great; when they are small, an occasional day may have many spots, but the average day is sure to have only a small area of spots. Fig. 6 presents Tables 10 and 11 graphically. It shows the amount of change in barometric gradients, that is, the instability of the weather on days with various "solar quadrant differences," and hence on days with varying areas of spottedness on the sun's margin. The higher the line the greater the barometric change as shown on the left; the figures at the top indicate the degree of solar activity, that is, the quadrant differences. All the days of the two periods, 1904-1909, when sunspots were numerous, and 1910-1913,

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[10] This is fully explained in Solar Disturbances and Terrestrial Weather, Mo. Weath. Rev., 1918. In that article it is shown that the closest relation between sunspots and the barometric gradients over the Atlantic Ocean is found when there are many spots on some parts of the sun's margin and few on others. More specifically, the sun's visible disk was divided into four quadrants by means of the solar equator and the meridian which happened to be in the center of the sun's disk on the day in question. Since the sunspots in the central parts of the sun's disk seem to have either no relation to the gradients or else a negative relation, as appears in Fig. 5, they were omitted. Then it was found that among the spots more than 30° from the sun's central meridian those in the northwest and southeast quadrants seem to have an opposite effect from those in the northeast and southwest quadrants. Accordingly a large series of comparisons was made between barometric gradients and "quadrant differences" or "solar differences," that is, the difference between the total areas of the sunspots more than 30° from the sun's central meridian in the N.W. plus S.E. quadrants and the similar areas in the N.E. plus S.W. quadrants. Further discussion of this complicated matter is postponed because it is desired to concentrate attention upon the fact that an excess of spots upon any part of the marginal portions of the sun's disk appears to be more effective in producing disturbances upon the earth than is a similar excess of spots near the sun's center. We shall see later that the quadrant differences are highly important and seem to have a sound physical basis.

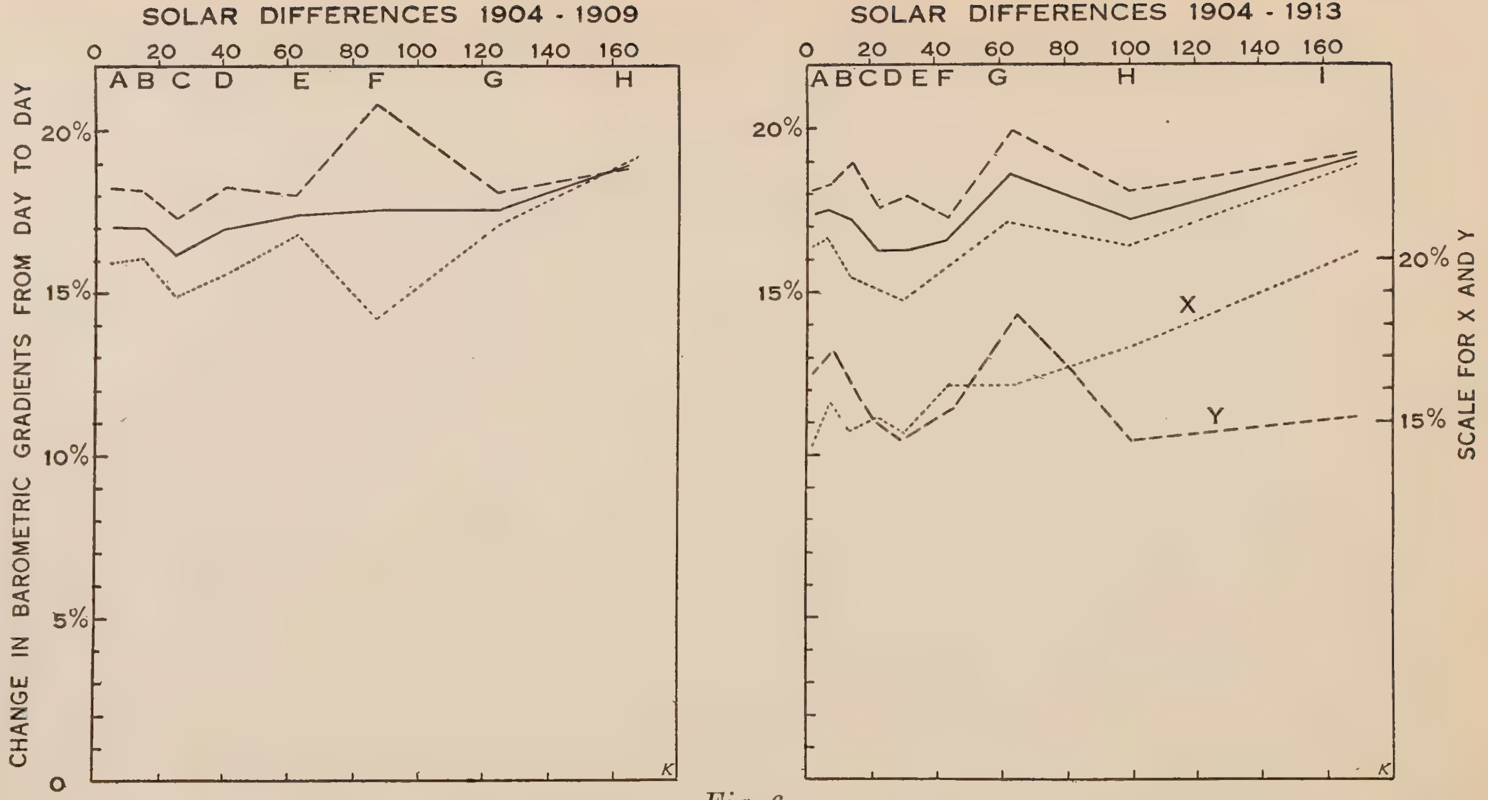

Fig. 6.

Changes in Barometric Gradients from one Day to the next, in Relation to Days having Varying Differences between the Areas of the Umbræ in (1) the NW.+SE. Quarters of the Sun's visible Disk, at a Distance of more than 30° from the Central Meridian, and (2) the NE.+SW. Quarters at the same Distance from the Meridian. (*Courtesy of the United States Weather Bureau.*)

.... changes in gradients in north section of North Atlantic Ocean, 1904-1909.
- - - - - - - - changes in gradients in south section of North Atlantic Ocean, 1904-1909.
——— average of .... and - - - - - - - -
X, changes in northern section, 1904-1907, when sunspots were abundant or increasing.
Y, changes in northern section, 1908-1913, when sunspots were scarce or decreasing.

when they were scarce, have been divided into groups on the basis of quadrant differences, that is, of activity on the margins of the sun's visible disk. In the left-hand part of Fig. 6, group A consists of 653 days having a quadrant difference of 10 or less, group B of 284 days with a difference of 11 to 20, and so up to group H, consisting of 156 days, with a difference of over 150. If solar activity is really responsible for changes in the weather, we should expect the daily change in gradients to increase from group A to group H.

In both parts of Fig. 6 the upper dash lines indicate the barometric variability of the southern section of the North Atlantic. Below these come solid lines representing the average for both sections of the Atlantic, and dotted lines for the northern section. According to these lines barometric variability appears to be greater in the southern section of the North Atlantic than in the northern. This is merely because the figures for gradients have been reduced to percentages of the monthly normals. In the left-hand part of Fig. 6 one of the prominent features is the marked rise of one curve and fall of the other between 80 and 100. This means that during the group of days marked F there happened to be an unusual number of storms with courses more southerly than the normal. They caused unusually great changes in the weather in the southern section of the North Atlantic where high pressure generally prevails, while the northern section was unusually free from such changes.

Taking the lines in the left-hand part of Fig. 6 separately and disregarding the minor fluctuations, we see that aside from the point F the dash line representing the variability of the weather in the southern section has a slight tendency to rise from left to right. The average change of gradients from day to day in groups A to D is

18 per cent, while in groups E to H it is 18.9 per cent. In the northern section, as appears in the dotted line, the rise from left to right is greater, being from 15.6 in groups A to D to 16.7 in groups E to H. Except for an accidental depression in group C, the combined line for the two sections rises rather steadily from 17 at the left end (group A) to 18.9 on the right (group H). Thus there is evidence that the greater the activity on the sun's margins, the greater the variability of the weather in the North Atlantic Ocean. This is especially true in the northern section, for there the variability in group A is only 15.9, while in group H it is 18.9, a difference of 19 per cent.

If instead of group H, which includes 156 days having quadrant differences of over 150, we take a smaller group of 87 days with quadrant differences of over 200, the average variability from day to day in the northern section of the North Atlantic rises from 18.9 to 19.1. This is 18 per cent above the general average, which is 16.2, and 20 per cent above group A. Among the 87 days of the group with greatest activity on the sun's margin, 43 show an increase in gradients, averaging 18.8, while 44 show a decrease averaging 19.4.

If a difference in solar activity for only a single day produces a terrestrial effect, a continuance of such a difference would presumably produce a greater effect. Therefore in Table 11 and in the right-hand part of Fig. 6 all the days from 1904 to 1913 are classified into nine groups according to the average difference between the pairs of solar quadrants during the period of four days ending with the day in question. In group A this average quadrant difference is five or less, in group B, six to ten, and so on up to group I, where the average differences are over 125. In spite of considerable irregularity the three upper lines in the right-hand part of Fig. 6 show a stronger upward tendency from left to right than do the corresponding lines in the left-hand part of the diagram.

Years of increasing and decreasing sunspots by no means act alike. This is evident from lines X and Y in Fig. 6. Line X pertains to the years 1904-1907, when sunspots were *increasing.* Line Y pertains to 1908-1913, when sunspots were *decreasing.* The zero point of X and Y, it will be noted, has been placed lower than that of the other lines in order to avoid overlapping. Curve X has a pronounced upward tendency. The right-hand end is more than 30 per cent higher than the left, and the irregularities are small. Curve Y, on the other hand, scarcely shows any distinct tendency either upward or downward. The average of groups A to E, to be sure, is 15.22 while that of F to I is 15.75. The high level of groups A and B in line Y suggests that here, just as in previous cases, we are confronted by what seems to be a contradiction; in general the greater the solar activity the greater the barometric disturbances, but when the sun's surface appears to become unusually quiet and a new period of disturbance receives its first impulse, this generalization breaks down.

TABLE 12

CONTRAST BETWEEN BAROMETRIC CHANGES ON DAYS WHEN SOLAR QUADRANT DIFFERENCES ARE GREATEST AND ON SUCCEEDING DAYS OF SLIGHT ACTIVITY

	Per cent
(1) Highest 138 days	29
(2) Highest 80 days	32
(3) Highest 25 days	47
(4) Highest 10 days	106

A final evidence of the intimate relation between solar activity and barometric pressure is found in Table 12. Here we are dealing with the days of greatest solar activity, as measured by quadrant differences. The column marked per cent shows the difference between the maximum daily change in barometric gradients during a solar disturbance and the minimum change a day or two after the end of the disturbance.

The rapidity with which these percentages increase is highly significant. So, too, is the low level to which the change in gradients falls at the minima representing the times when this particular type of solar effect is slight, either because of the absence of spots or because the spots are concentrated near the sun's center. Apparently when the quadrant differences are greatest or the accompanying weather-producing agencies of the sun's surface are particularly active, the North Atlantic Ocean alternates rapidly between periods of low gradients accompanied by remarkably little change of weather and periods of high gradients accompanied by storms.

The truth of this conclusion may be illustrated in another way, as is seen in Fig. 7. Here 20 sunspot groups have been selected, because they gave rise to large quadrant differences when they appeared on the sun's eastern margin and again when they disappeared on the western margin. Ten of these groups were in the sun's northern hemisphere and 10 in the southern. The change in barometric gradients in the northern section of the North Atlantic Ocean in respect to each of these periods appears in Table 13 and is plotted in Fig. 7. The day marked 0 is the day on which the solar disturbances first became evident. When spots were abundant in the sun's southern hemisphere, line A, the gradients rose to a maximum within one or two days after the contrast between the two sides

TAB

CHANGES IN BAROMETRIC GRADIENTS IN NORTHERN SE
WHEN 20 ACTIVE GROUPS OF SUNSPOTS

	Days before appearance of spots										
	8	*7*	*6*	*5*	*4*	*3*	*2*	*1*	*0*	*1*	*2*
Spots south of solar equator:											
Average change	15.0	14.1	26.1	13.8	12.5	14.2	14.9	17.0	15.2	21.2	21.6
Smoothed average . . .		17.3	20.0	16.6	13.3	14.0	15.3	16.0	17.2	19.8	**20.0**
Spots north of solar equator:											
Average change	20.7	20.5	15.6	10.9	15.8	16.9	18.1	14.5	18.3	13.3	20.1
Smoothed average . . .		17.6	15.6	13.3	14.8	16.9	16.9	16.4	16.1	16.3	17.6
North and South:											
Smoothed average change .		18.3	17.8	14.9	14.0	15.4	16.1	16.2	16.6	18.0	**18.8**

E 13

TION OF NORTH ATLANTIC IN REFERENCE TO PERIODS ASSED ACROSS THE SUN'S DISK, 1904-1913

Days after appearance of spots																
3	*4*	*5*	*6*	*7*	*8*	*9*	*10*	*11*	*12*	*13*	*14*	*15*	*16*	*17*	*18*	*19*
.4	18.9	13.7	16.2	11.5	11.4	13.3	13.5	11.9	18.3	14.2	23.0	17.2	22.8	19.4	17.6	25.2
.6	16.8	15.6	14.4	12.6	11.9	12.8	13.0	14.0	15.7	17.4	19.3	20.1	**20.6**	19.0	20.0	
.9	22.0	14.9	20.6	16.5	15.7	14.7	19.5	16.6	16.9	13.8	22.7	14.1	13.5	9.8	14.0	17.1
.9	**18.9**	18.1	18.2	17.3	15.7	16.2	17.6	17.4	16.1	16.8	**18.3**	16.1	12.7	11.8	13.7	
.4	17.9	16.9	16.3	15.0	13.8	14.5	15.3	15.6	15.9	17.1	**18.9**	18.1	16.6	15.8	16.8	

of the sun became great. Six or seven days later, when the spots were near the sun's center, the change in barometric gradients fell very low, and the weather was comparatively steady. After another eight days the weather again became disturbed, and this disturbance apparently was

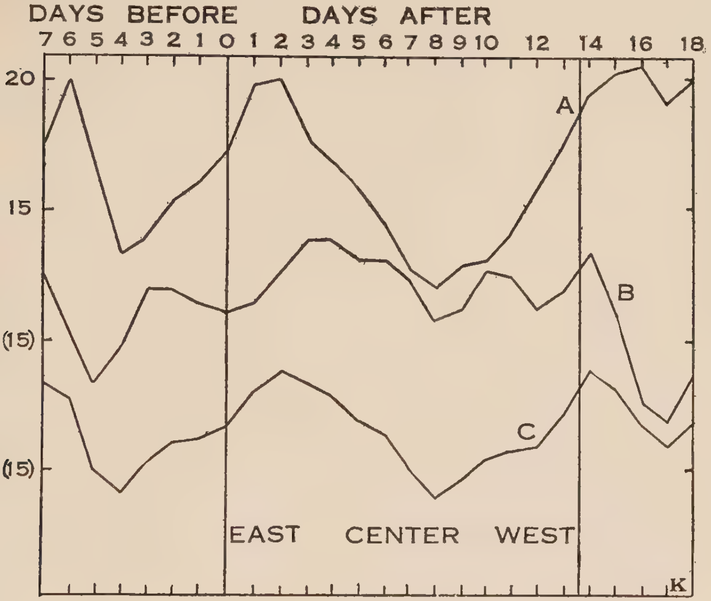

Fig. 7.

Changes in Barometric Gradients as Sunspot Groups pass from the Eastern to the Western Margin of the Sun.

(*Courtesy of the United States Weather Bureau.*)

A, southern groups. B, northern groups. C, both groups combined.

connected with the presence of the spots on the sun's western margin. The interval from one maximum to the other in this case is 14 days or about half of the sun's period of rotation. It suggests that the maximum effect is produced when the spots are almost on the sun's limb.

Line B, Fig. 7, suggests that spots in the sun's northern hemisphere have less effect than those in the southern, but the number of cases is not large enough to be conclusive. During the periods while the spots were visible the average intensity of the barometric changes in the North Atlantic Ocean was higher than either before or after. They reached a maximum three days after the spots appeared on the sun's eastern margin, fell to a minimum when the spots were in the sun's center, and rose again to a maximum when the spots reached the sun's western margin. On combining the apparent effect of the two sets of sunspot groups, as is done in line C, Fig. 7, we obtain a regular curve which confirms other data in indicating that when sunspots appear on the sun's eastern margin, the weather of the North Atlantic Ocean becomes unsettled; when the spots reach the center of the sun's visible disk the weather tends to become steady; and when the spots pass out of sight on the sun's western margin there is again a period of unsettled weather. This conclusion must be taken in conjunction with the previous conclusions that the earth's surface temperature varies inversely as the number of sunspots, while storminess varies directly as the sunspots. The three conclusions seem to afford a strong presumption that variations in solar activity are one of the causes of changes in the weather.

CHAPTER IV

THE PARADOX OF A HOT SUN AND A COOL EARTH[1]

IN a preceding chapter we saw that when the solar constant is high the average temperature of the earth's surface is likely to be low. Two explanations of this peculiar phenomenon demand attention. One ascribes it to the formation of ozone in the upper air, and the other to an increase in the rapidity of the atmospheric circulation. In advancing the first hypothesis, Humphreys[2] points out that under conditions such as prevail in the cold, dry, upper layers of the atmosphere, the sun's ultra-violet rays have a tendency to convert oxygen into ozone. Ozone is more transparent to radiation of short wave lengths (light) than to that of long wave lengths. Hence, while admitting the short wave lengths of the solar radiation, it checks the long heat waves which the earth radiates into space, and acts as a blanket which retains the sun's energy after it has been converted into heat. When sunspots are numerous, and the solar constant is high, the percentage of ultra-violet rays in the sunlight is inferred by Humphreys to diminish, while with a low solar constant the opposite supposedly takes place.[2a] Hence at times of few sunspots the formation of ozone at high levels is supposed to cause a rise of temperature throughout the earth's atmosphere.

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[1] Dr. Stephen S. Visher and Dr. Charles F. Brooks have contributed to this chapter so materially that the ensuing pages may be regarded as due to them as much as to the author.

[2] W. J. Humphreys: Physics of the Air, 1920.

[2a] See note at end of this chapter.

Theoretically, this may be possible, although, as Humphreys takes care to point out, it has no observational support. As yet, however, we have no means of knowing whether the assigned cause is adequate to produce the observed effect. This effect, it will be remembered, involves in the first place a raising of the mean temperature of the air to the extent of 0.6°C. in equatorial regions and of 0.4°C. in middle latitudes at times of few sunspots. It also involves much more, for the lowering of temperature due to diminished solar radiation at times of few spots must be neutralized before there can be any rise of temperature. On the basis of his measurements of the solar constant, Abbot[3] concludes that the diminution is enough to cause a difference of 2.5° between sunspot maxima and minima. Hence the total effect ascribed to ozone must be perhaps 3°C. This seems small at first thought, but its real magnitude becomes apparent when we recall that taking the earth as a whole, the position of the snow line and other geological evidences indicate that during the last glacial period the temperature averaged only 5° to 6°C. lower than now. The production of sufficient ozone to cause so large a change of temperature seems to demand a rather large difference in the composition of the solar radiation at times of many sunspots and of few. In addition to this, Clayton[4] has shown that at tropical and subtropical stations where the rainfall and cloudiness are slight, the mean temperature of the air is higher at sunspot maxima than at sunspot minima. He finds that the same is true north of latitude 60°. Such a local distribution of high temperature at times of many sunspots could scarcely be due to a general veil of ozone, for all parts of the upper air must in the long run have essentially the

[3] C. G. Abbot: The Sun and the Weather, Scientific Monthly, Nov., 1917.

[4] H. H. Clayton: World Weather, Macmillan Company, New York, 1923.

same proportion of the various atmospheric constituents. Again, at sunspot maxima the mean pressure throughout the tropics is low according to Clayton, a fact which implies that the atmosphere as a whole is relatively warm, even though it may be cool at the earth's surface.

These considerations do not mean that ozone is wholly ruled out as a factor in raising the earth's temperature at times of sunspot minima. But until the ozone hypothesis is based on observational data, its importance is doubtful. This conclusion is the more warranted because other agencies, whose effect has long been known and measured, appear to be sufficient to explain the change in temperature between sunspot maxima and minima.

Among these other agencies are cyclonic storms. Let us consider what would happen to the temperature of the air near the earth's surface if some agency were to increase their severity and frequency. In the first place cyclonic storms are accompanied by clouds. The reflecting power of clouds is great, rising to 78 per cent when the clouds are dense, according to recent observations by Aldrich.[5] Thus the reflection of sunlight due to a relatively small increase in storminess might balance the extra heat received from the sun in other regions. Second, a more rapid circulation of the air such as would accompany or cause increased cyclonic activity must mean that the air on the whole is drier than would otherwise be the case. Nevertheless, the total amount of evaporation may increase because the "capacity" of the air for moisture will be relatively great and new supplies of dry air will constantly be brought by the rapid atmospheric circulation. Thus even though the sun supplies more heat than usual when sunspots and storminess are at a maximum, the dryness of the air in clear, anticyclonic areas may allow all of the extra solar heat in those regions to escape into space, while the cloudiness in the cyclonic areas may prevent much of the solar heat there from ever reaching the earth's surface.

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[5] L. B. Aldrich: The reflecting power of clouds, Smiths. Misc. Coll., Vol. 69, No. 10, Washington, 1919. Abstr. in Mo. Weath. Rev., Vol. 47, 1919, p. 154.

In addition to this, cyclonic storms carry a great amount of warm moist air to high levels. Most of this air comes from the equatorial side of the storms; in the United States, for example, it is brought by the southerly winds which commonly precede rain. In the center of the storm the air is carried far aloft and takes with it large quantities of heat, chiefly in the form of the latent heat of vaporized water. When the vapor condenses into clouds or rain, most of the heat which it thus gives up serves to retard the cooling of the upper air, and its escape into space is easier than if it were liberated under similar circumstances at a lower level. After the warm moist air of the storm centers has risen high enough it becomes very cold and dry. When this air descends in a high pressure area it is warmed adiabatically, that is, by the compression to which it is subjected. Nevertheless, its extreme dryness may allow it to radiate its heat so rapidly that it becomes very cold. The relation between the rate of radiation and the vapor pressure of the air is very close.[6] Finally this cold air forces its way in toward the center of a low pressure area and there pushes under the warm moist air that comes from the equatorial side and forces it to rise. The more numerous the cyclonic storms, the greater the amount of warm air that is forced upward to such a height that its heat may readily be lost by radiation into space. Thus increased storminess accompanying an increased general activity of the atmospheric circulation might cool the earth's surface through such increased radiation as well as by the other methods mentioned above. The rest of this chapter is largely a detailed consideration of this point.

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[6] H. H. Kimball: Solar and Sky Radiation during February, 1918, Mo. Weath. Rev., Vol. 46, No. 2, Feb., 1918, p. 56.

Although the temperature of the earth's surface depends on the balance of many intermediate factors such as evaporation, condensation, and movements of air and water, the final result for the earth as a whole depends essentially on the balance between the radiation received from the sun, and the heat lost through conduction and outward radiation. If either of these suffers a change, the temperature of the earth's surface must also change. Let us suppose that one of them, namely, the solar radiation, remains constant. Then let us inquire whether a change in the number and intensity of storms would cause any change in the other factor, that is, in the loss of heat by conduction and radiation.

The rate at which heat is conducted away from any part of the earth's surface depends largely on the movement of the air. Since conduction takes place only between surfaces having a difference of temperature, and since stagnant air soon assumes approximately the temperature of the surface against which it lies, conduction in still air almost ceases except as surrounding surfaces change their temperature. When the air is in motion the conduction of heat increases under ordinary daytime conditions. This is because the new air thus brought into contact with the earth's surface almost always has a lower temperature than the air which has long been in contact with the surface. In the daytime, when the sun is shining, this is obviously true. It appears also to be true when average conditions at all hours and seasons are considered, for the thing that is heated, namely, the air, must average cooler than the thing from which it primarily derives its heat, that is, the earth's surface. Hence, so far as conduction alone is concerned, an intensification of storminess and an increase in the general rate of atmospheric circulation must tend to cool the earth's surface.

The movement of the air influences radiation much as it does conduction. The net loss of heat by radiation depends upon the balance between the earth's own outward radiation and all the heat which it receives by radiation or reflection from other sources, including the air. Most of the heat received through atmospheric radiation and reflection comes from water vapor, clouds, fog, haze, dust, and carbon dioxide. These materials radiate back to the earth a considerable part of the heat which they receive from it, for radiation takes place equally in all directions. Clouds and fog also reflect heat rays downward as well as reradiate them. All these constituents of the atmosphere are largely limited to the lower air. In fact they appear to exert more than half their total effect below a height of perhaps 3000 feet. This is true of the blanketing effect which they produce by absorbing the heat radiated outward from the earth and radiating or reflecting part of that same heat back again. When heated air is carried above the layer where the blanketing process is chiefly effective, some part of the heat which under other circumstances might be radiated or reflected back to the earth is lost by being radiated or reflected outward into space. If there is an acceleration of the general circulation of the earth's atmosphere,—a circulation composed of complete circuits including both vertical and horizontal movements,—there must be a corresponding increase in the amount of air that is carried in a given time beyond the levels where clouds are most effective as a blanketing agency. Thus the average temperature of the earth's surface may be reduced, although this reduction may be less significant than that due to radiation in dry anticyclones and reflection in cloudy cyclones.

Here is another way of looking at the matter. Above an area of low pressure the air in the lofty isothermal layer is usually warmer than at the same level above an anticyclonic area, and also warmer than would be expected if the temperature depended solely on adiabatic cooling. For example, in summer, according to Table 1 and Fig. 18 in Humphreys' *Physics of the Air,* the temperature of the isothermal layer above 38 areas of low pressure averaged 7° or 8°C. higher than the temperature at the same level above 32 high pressure areas. This is explained by Humphreys as follows (p. 56):

> Since the curves of Figs. 17 and 18 are the averages of a number of flights, it may be approximately correct, in an effort to account for their differences, to start with something like average conditions and trace the consequences. Let these conditions be a moist atmosphere in the one case and a dry one in the other, each having the same temperature as the other at all levels. The moist atmosphere, because a better radiator than the dry, will, under the same conditions of exposure and at the end of the same interval of time, cool to a lower temperature, but in so doing—that is, in getting rid of its own heat most rapidly—it at the same time supplies heat at greater rate to any neighboring region that receives it by radiation only. Therefore when the lower atmosphere is moist it will, under like conditions, radiate heat most rapidly to and through the always dry air of the isothermal region, and while getting cold itself will at the same time warm this region to a temperature above its average. On the contrary, in the region of a high barometer the lower air, being relatively dry and therefore a poor radiator, will conserve its own temperature, but in so doing will allow the isothermal region to get cold in comparison with its temperature during the prevalence of a low at the same season.

Put in another way this means that convection allows a certain amount of heat to be taken away from the lower air in areas of low pressure and to raise the temperature of the air in the isothermal layer so that it is 7° or 8° above the temperature of the corresponding air over areas of high pressure. An increase in the number and intensity of cyclonic storms, especially if accompanied by unusual clearness in the high pressure areas, as seems to be the case when sunspots are numerous, would obviously serve still further to lower the temperature of the lower air and raise that of the isothermal layer.

When air that has thus lost heat by radiation finally descends it may produce any one of three results: (1) It may be relatively warm when it reaches the earth's surface. This will happen if the downward movement is so rapid that adiabatic heating due to compression is greater than the loss of heat by the air because of its own radiation, and if the air is not able to cool itself by picking up much moisture. A well-known example of this is the so-called "free-air foehn," a warm, dry, and rapidly descending wind, comparable to the mountainside foehn of Switzerland and the chinook of the western United States. A descent rapid enough to cause such a wind often occurs locally on high mountains in strongly anticyclonic areas. (2) The air may reach the earth's surface at essentially the same temperature as the air already there and thus produce no appreciable effect. This happens when the air descends so slowly that the radiation which it gives out and that which it receives, from the earth chiefly, have time to produce a state of equilibrium no matter how much moisture the air may evaporate. In this case it makes no difference how long or sinuous a course the air pursues in its descent. Such conditions may possibly prevail in weak high pressure areas where the movement of the air is sluggish. (3) The air may reach the earth's surface at such a temperature that it has a cooling effect. This happens where the air descends diagonally in such a way that it passes from higher to lower latitudes; or else where the air in descending has an opportunity to pick up enough moisture so that it has nearly as much as it had when it began to rise in some other latitude. Movements of this kind are common in high pressure areas and join with rapid radiation in explaining why the lowest layers of the air are normally cooler in highs than in lows in the same region.

From these three cases it is clear that the air descending in a high may produce very different effects at different places or at different times in the same place. Nevertheless, the total effect of the descent of such air and of the radiation permitted by its clearness is usually to cool the surface of the earth.

Now suppose that storminess is increased by some agency whose character need not here concern us. Less air than formerly will descend so slowly that it reaches the earth's surface at essentially the same temperature as the air already there. On the other hand, the air will more frequently descend in such a way that it produces either hot foehn winds or cold waves. Extreme temperatures will thus be more frequent than with a slower circulation, although it does not necessarily follow that the extremes themselves will be any greater than before. Hence one of the results of a more rapid circulation would presumably be to increase the variability of a climate. Nevertheless, the cold waves should more than balance the warm winds, for the net effect, as we have seen, will apparently be a lowering of temperature.

It is not yet possible to determine precisely the average degree of cooling due to the radiation of heat into space by air that descends in anticyclones. It seems highly important when one compares a temperature of 50°F. one morning with 10° twenty-four hours later under the influence of descending air from the northwest. Of course this difference largely represents merely the difference in latitude between the places where the two bodies of air started. The important point, however, is that the warm air of the first morning disappears chiefly by being pushed upward by the heavier cold air from the northwest. It is not pushed on toward the east by this wind, as is shown by the suddenness of the change of temperature which occurs as soon as the northwest winds commence to blow. Since it is pushed upward, its high temperature no longer benefits the lower air, even though the cooling of the upward moving air may be delayed by the condensation of water vapor. Thus cyclonic storms remove heat from the earth's immediate surface with which we are chiefly concerned. The increased frequency and severity of such losses appear to join with increased cloudiness and rainfall in low pressure areas and increased dryness and radiation in high pressure areas in causing the storminess which prevails at times of many sunspots to lower the earth's mean temperature in middle latitudes in spite of the relatively abundant solar radiation. In polar regions, however, increased storminess may mean higher temperature at the surface, for the usual cold layer next to the ground is not allowed to accumulate to the same degree as before.

In order to gain a still clearer idea of the effect of increased storminess upon the temperature of the lower air, let us consider it in more detail with reference to (1) evaporation of water vapor, (2) cloudiness, (3) the latitudinal distance through which heat is carried by storms, (4) local convection, and (5) rainfall.

1. The rate of evaporation of water from a moist sur-

face increases rapidly with increase in wind velocity. So far as our present problem is concerned, the difference of temperature, about half a degree C., between sunspot maxima and minima, produces a negligible effect on evaporation when compared with the effect of the movement of the air and the relatively low vapor content thus arising at high altitudes when the air in cyclones wells upward to unusual heights, and at low altitudes where such air descends in high pressure areas. In years of both minimum and maximum sunspots the average air is far below the saturation point, so that except under special conditions evaporation is usually possible. The rate of evaporation under such conditions is greatly influenced by the velocity of the wind. According to C. E. P. Brooks[7] the effect of wind is as follows:

(A) At 10 miles an hour an unsaturated wind evaporates 17 per cent more than at 5 miles.

(B) At 15 miles an hour an unsaturated wind evaporates 14 per cent more than at 10 miles.

(C) At 25 miles an hour an unsaturated wind evaporates nearly 11 per cent more than at 20 miles.

If the velocity of the winds increases, as appears to be the case when storms are numerous, they will evaporate more water than formerly, and heat will be taken from the lower air. The heat will be carried upward by convection, and thus will have a chance to escape into space.

2. Before leaving the subject of atmospheric moisture it may be well to meet more fully a possible objection to our conclusion as to the cooling of the earth's surface by an increase in storminess. The objector may say that increased cloudiness accompanying unusual storminess might warm the lower air instead of cooling it. As every-

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[7] C. E. P. Brooks: The Meteorological Conditions of an Ice Sheet, Quarterly Jour. Royal Meteorol. Soc., Vol. XL, 1914, p. 65.

one knows, on clear nights frost is much more probable than on cloudy nights. When the absolute humidity is high, and especially when the air is cloudy, the earth's heat is not radiated away so fast as when the air is clear and dry. The universality of this phenomenon raises the question whether the cooling effect of cloudiness by day is greater than the warming effect at night. In other words, how does the reflection of solar radiation upward from the clouds by day compare with the downward reflection and radiation from the bottom of the clouds at night?[8]

It should be noted at the outset that the ratio between the reflection of sunlight from the tops of clouds, and their retention of heat from below varies greatly according to latitude. In high latitudes where winds and currents bring heat from warmer regions, the blanketing effect of cloudiness ordinarily outweighs the effect of the clouds in shutting out solar radiation. But the area where this is true is much smaller than the area in low latitudes where the opposite may be the case. The matter can be tested either mathematically or empirically. Both methods meet with many complications. Doubtless the mathematical method will in the end prove the most reliable, but with our present scanty knowledge it requires a great number of assumptions which expose it to constant error. Moreover, the process of calculation is so intricate that even the most experienced scientist may make mistakes. Therefore it seems wiser to adhere to the method which prevails throughout this book—that is, let us discover what is actually happening, regardless of any theory.

In order to determine the relation of clouds to temperature, I have made use of four charts in Bartholomew's *Atlas of Meteorology*. Two show the mean cloudiness of the world in January and July. The cloudiness is expressed in tenths of the sky which are obscured. The other two charts show anomalies of temperature in January and July. They indicate the extent to which the temperature departs from the mean of its latitude at the particular time in question. For instance, if there were no winds, storms, and ocean currents, the west coast of Ireland and the east coast of Labrador would have the same temperature. As a matter of fact, in January Ireland is more than 30°F. warmer than the mean of its latitude, while the east coast of Labrador is 10°F. colder than the mean. These figures constitute the anomalies for the respective regions during January. The parts of the earth more than 30° from the equator are subject to extreme anomalies, partly because of the great size of the continents and partly because of the ocean currents. Therefore the present investigation has been restricted to the area within 30° of the equator.

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[8] The following discussion of moisture and cloudiness is taken largely from "The Solar Hypothesis of Climatic Changes," Bull. Geol. Soc. Am., Vol. 25, 1914.

In the charts of cloudiness and of anomalies of temperature use has been made of the 126 points where the equator and the parallels of 10°, 20°, and 30° north and south intersect the meridians of 0°, 20°, 40°, and so on at intervals of 20° around the world. For each point the anomaly and the cloudiness in January and July have been taken, and the figures have been combined to show whether increased cloudiness is accompanied by a rise or fall of temperature. Three different methods have been pursued. In the first place all the points have been divided into groups on the basis of their anomaly. The first group, A in Table 14, includes places showing an anomaly of —10°F. or more. The second, B, includes places showing an anomaly of —9.9° to —5.0°, the third from —4.9° to —2.6°, and so on up to a plus anomaly of 10° or more. The results are shown in Table 14 and Fig. 8. Taking oceans and lands together, it appears that in the small number of cases included in group A, where the temperature falls most below what would be expected, the average cloudiness is 5.1, which means that the sky is covered with clouds a trifle more than half the time. In the next three groups the cloudiness jumps back and forth, as is seen in the middle line of Fig. 8, but never departs far from 5. Then, beginning with group E, which includes all places having an anomaly of less than 1°, we see that there is a steady decrease in cloudiness as the anomaly becomes greater in the plus direction. In other words, where the temperature is lower than would be expected, there is a fairly high degree of cloudiness, whereas where the temperature is higher than would be expected there is relatively little cloudiness. This looks as if there were a distinct relation between temperature and cloudiness. Over

TABLE 14

CLOUDINESS AT PLACES HAVING VARIOUS TEMPERATURE ANOMALIES BETWEEN 30° SOUTH AND 30° NORTH FOR THE MONTHS OF JANUARY AND JULY

	Whole world		*Land*		*Ocean*	
Temperature anomaly	*No. of cases*	*Average cloudiness*	*No. of cases*	*Average cloudiness*	*No. of cases*	*Average cloudiness*
A, —10°F. or more	5	5.1	..	..	4	5.0
B, —5° to —9.9°	25	4.68	..	..	23	4.63
C, —2.6° to —4.9°	31	5.24	6*	4.58*	28	5.39
D, —1.0° to —2.5°	54	4.72	16	3.63	38	5.18
E, —0.9° to 0.9°	26	5.06	5	5.0	21	5.07
F, 1.0° to 2.5°	54	4.99	18	4.67	36	5.15
G, 2.6° to 4.9°	33	4.80	18	4.39	15	5.30
H, 5.0° to 9.9°	16	4.56	12	4.58	5†	4.90†
I, 10° or more	8	3.19	7	2.71	..	..

* A, B, and C. † H and I.

the ocean this relationship is not very clear, as appears in the upper curve of Fig. 8. Over the lands, however, as appears in the lower curve, it is distinct, although a marked irregularity occurs at D, and there are almost no

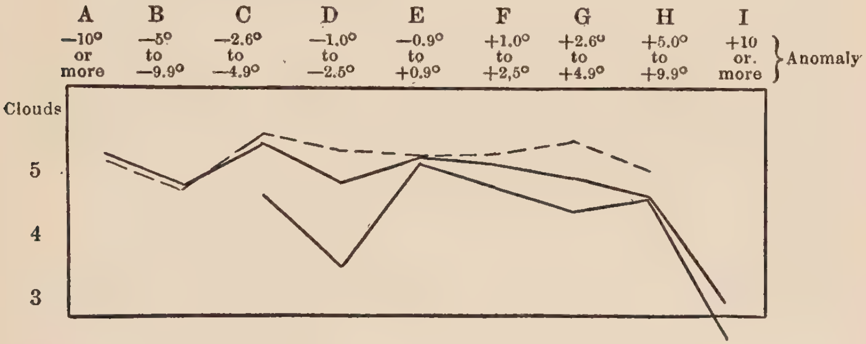

Fig. 8.

Cloudiness in Regions having Various Temperature Anomalies. See Table 14.

Upper dash line=water alone.
Upper solid line=land and water.
Lower solid line=land alone.

data for groups A and B. There can be little question that over the lands an excess of heat is found where the cloudiness is least.

Let us test the matter in another way. In Table 15 our different points of observation are grouped according to the degree of cloudiness instead of according to the anomaly, as in Table 14. The first group includes all points having a cloudiness of 1 or less, the next those having a cloudiness of from 1 to 2, and so on up to those having from 7 to 8. The meaning of Table 15 can readily be grasped from Fig. 9. In the upper line it is evident that over the lands an increase of cloudiness is accompanied by a fairly steady decline in the anomaly. Where the cloudiness is between 1 and 2 the temperature is on an

TABLE 15

TEMPERATURE ANOMALIES AT PLACES HAVING VARIOUS DEGREES OF CLOUDINESS BETWEEN LATITUDES 30° SOUTH AND 30° NORTH FOR THE MONTHS OF JANUARY AND JULY

	Entire area		*Land area*		*Oceanic area*	
Degree of cloudiness	*Basis*	*Average anomaly*	*Basis*	*Average anomaly*	*Basis*	*Average anomaly*
0 —1	3	(+5.33°)	3	(+5.33°)	0	....
1.1—2.0	16	+3.33°	14	+3.89°	2	....
2.1—3.0	16	+1.78°	13	+2.35°	3	(—0.67°)
3.1—4.0	42	—0.82°	12	+3.17°	30	—2.42°
4.1—5.0	75	—0.52°	18	+1.11°	57	—1.04°
5.1—6.0	58	—1.03°	12	±0.00°	46	—1.29°
6.1—7.0	28	—0.14°	10	+1.40°	28	—0.70°
7.1—8.0	4	(+4.9°)	3	(+4.66°)	1	....

average about 4°F. higher than the mean for the latitude. Where the cloudiness rises to 4 or more, on the other hand, the anomaly drops to plus 1, or even to 0. The oceans, on the contrary, show a slight tendency in the opposite direction. They are of far less importance than the lands, however, for their temperature depends largely on the transportation of heat by ocean currents, or on the upwelling of cold water from below. Thus an anomaly which actually arises in a sunny region may be transported toward a cloudy region, and may there be concentrated so that it appears more important than at its place of origin. Indeed, the place of origin may actually be cooled by the rapid removal of heat. If we take the lands alone we find that the method employed in Table 15 and Fig. 9 points toward the conclusion that the presence of clouds is associated with relatively low temperature at the earth's surface.

In the two preceding methods we have compared different parts of the earth with one another, and hence have been liable to error because of the great variety of relief, currents, winds, and other physical characteristics which prevail in one region or another. Let us now compare the conditions of each region at different times of the year. The results appear in Table 16. Among the 126 points used in our calculations, 110 show a distinct change of cloudiness from January to July. In 59 cases the cloudiness decreases and in 51 it increases. Over the lands the average temperature is higher in July than in January, no matter whether the cloudiness is greater or less, while over the oceans the reverse is true. This, however, does not prevent us from testing the matter, for we can determine whether the cloudy places have a greater or less increase or decrease of temperature than do the ones with less clouds. Testing the matter in this way, we find that on an average the land stations where the cloudiness of July exceeds that of January have an anomaly +1.3°F. greater in July than in January. On the other hand, the stations where the cloudiness of July falls below that of

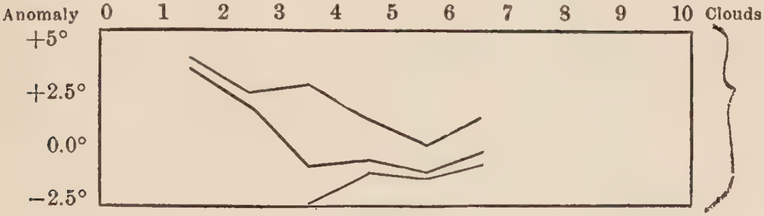

Fig. 9.

Temperature Anomalies for Various Degrees of Cloudiness. See Table 15.

Upper line=land areas.
Lower line=oceanic areas.
Middle line=oceans and land combined.

TABLE 16

COMPARISON OF CHANGES OF CLOUDINESS FROM JANUARY TO JULY WITH CHANGES OF TEMPERATURE ANOMALY FROM JANUARY TO JULY, BETWEEN 30° SOUTH AND 30° NORTH

	Area in per cent of whole	*Average change of cloudiness from January to July*	*Average change of anomaly from January to July*
Whole world:			
Regions with same cloudiness in January and July	12.0	0.00	+2.59°
Regions with less cloudiness in January than in July	40.0	+1.37	—0.06°
Regions with more cloudiness in January than in July	48.0	—1.61	—0.35°
Land:			
Regions with less cloudiness in January than in July	10.2	—1.35	+1.92°
Regions with more cloudiness in January than in July	19.4	+1.96	+1.33°
Ocean:			
Regions with less cloudiness in January than in July	30.0	—1.38	—0.74°
Regions with more cloudiness in January than in July	28.4	+1.28	—1.49°

Average difference associated with clouds, 0.70°.

January have an anomaly +1.9°F. greater in the later month than in the earlier. The difference between these two figures is 0.6°F. If there were no increase in cloudiness from January to July in the first group of places the temperature would apparently rise to this extent—that is, 0.6°—higher than it actually does. In the oceanic areas the result is similar. Here the places which show an increase of cloudiness, show a lowering of their anomaly to the extent of —1.5°, while those which have a decrease of cloudiness show a lowering of their anomaly only to the extent of —0.7°F. The difference is 0.8°F. The meaning of these facts is that where cloudiness increases, the temperature is lower than it would otherwise be to the extent of 0.8°F. over the oceans and 0.6°F. over the lands. Making due allowance for the difference in the area of the land and the sea, this gives us an average decrease of temperature amounting to 0.7°F. The amount by which the cloudiness changes on both land and sea is on an average about 1.5 on a scale of 10, but since the change is plus in one case and minus in the other the difference between the extremes is 3. Hence an increase of 4.2 in cloudiness would apparently be accompanied by a fall of 1°F. in temperature.

The preceding discussion shows that at present the net effect of an increase in cloudiness in low latitudes is a decline of temperature. Hence we conclude that the increased body of clouds actually reflects so much sunlight that the earth's surface becomes cooler in spite of the fact that the clouds hinder the radiation of heat away from the earth. The amount of cooling thus occasioned is not large, but it coöperates with similar effects arising from increased convection and evaporation. The chief importance of the matter lies in its indication that at present in low latitudes the retention of heat by clouds, which is the only important positive factor in raising the temperature of the earth's surface under our assumed conditions of more rapid atmospheric circulation, is not able to counteract the factors of an opposite character which diminish the temperature.

In middle latitudes it seems probable that cloudiness *per se* exerts a cooling effect in summer which is the season when a hotter sun would be most felt if cloudiness did not shut it out. In winter, on the contrary, increased cloudiness apparently acts as in polar latitudes and raises the temperature, for outward radiation is then primarily in control. As a matter of fact the relative amount of storminess and presumably of cloudiness in middle latitudes at sunspot maxima and minima varies greatly from season to season as well as from place to place, as may be seen in Figs. 23 to 26 in the next chapter. On the whole the middle latitudes appear to be transitional between low latitudes where cloudiness lowers the temperature by keeping out the sunlight and high latitudes where cloudiness raises the temperature by keeping in the earth's outward radiation.

3. In addition to its effect on evaporation and cloudiness, a rapid atmospheric circulation tends to lower the temperature of the earth's surface because violent storms draw air from greater distances than do weak storms. In the northern hemisphere, for example, the southerly winds on the eastern side of a low not only carry much more heat away from the low latitudes when storms are strong than when they are weak, but draw it from greater distances. Under the same circumstances much cold air is drawn from exceptionally high subpolar latitudes by the northwest winds on the westward side of the low pressure area. The air from low latitudes is indeed cooled while that from high latitudes is warmed as it moves toward a cyclone, but the faster the movement of the air the less effective is this change of temperature. Moreover, the farther the air moves at any given rate of speed, the greater the possibilities of a contrast between its temperature and that of the place to which it goes. Thus

under a forced cyclonic circulation the result is not merely that a great body of warm air is carried into the centers of storms and there raised aloft by inblowing cold air, but also that before the air rises its movements lower the temperature in low latitudes and raise it in higher latitudes. But the higher the latitude in which air of a given temperature is found, the more quickly it loses heat. This is chiefly because the surrounding air and the earth are cooler than under similar conditions in lower latitudes. Warm air in high latitudes is able to cool by radiation more rapidly than can cool air in low latitudes, for the radiation varies as the difference between the fourth powers of the absolute temperatures of the radiating and receiving bodies. The difference between the fourth powers of 290° and 300° (absolute temperature) is 41.2 per cent greater than between the fourth powers of 260° and 270°. Furthermore, with equal waves of warm and cold air spreading in opposite directions the cold air will lie in contact with the ground over larger areas than the warm, for while the cold air tends to hug the ground in entering warm regions, the warm air tends to rise over cool air or to become separated from the ground by a layer of cooled air. Thus the net effect of rapid circulation and of movements of the air through long distances north and south is a reduction of the mean temperature of the earth's surface.

4. Local convection is another means of cooling the earth's surface which is intensified by an increase in the strength of the winds. In local convection due to heat air rises only when it is forced to do so by being crowded up by colder air. When there is no general circulation, heated air may accumulate near the earth's surface. In times of a rapid general circulation and increased storminess this happens less frequently than at other times, for with in-

creased storminess there is more likelihood that movements of colder air will force the warm surface air to rise. Air in upward convectional motion is cooler than surface air not so moving. On the basis of Compan's experiments, Abbot[9] states that the loss of heat by convection is increased threefold by a breeze of three meters per second (6.7 miles per hour) as compared with the rate in still air. The more the turbulence at the surface, the less is the passing air warmed by that surface. At the same time the greater turbulence carries away more heat from the surface. Thus both the air and the surface are cooled.

5. Clayton[10] finds an increase of rainfall in tropical regions when sunspots are numerous. Hence he attributes a large part of the cooling of the air in tropical regions at sunspot maxima to the increased rainfall. The rain falls from an elevation where the temperature is from 5° to 10°C. lower than at the surface and brings its low temperature with it, thus lowering the temperature of the surface air. Thus anything which increases the amount of rainfall would to that extent lower the mean temperature. The increased rainfall at times of many sunspots may have some connection with the apparent rise in the number of cyclones. Certain it is that most tropical cyclones cause heavy rainfall.[11]

The gist of our discussion of a hot sun and a cool earth lies in this: When, but not necessarily because, the sun is hot the barometric gradients are strengthened, the rapidity of the earth's atmospheric circulation increases, and the number of cyclonic storms shows an augmentation. The increase in tropical cyclones is possibly greater proportionally, but by no means absolutely, than in the storms of middle latitudes. This may help to account for the slightly greater decrease in temperature in low than in middle latitudes at sunspot maxima. Relatively speaking, the increase in wind velocity and storminess at sunspot maxima seems to be more marked than the diminution of temperature. The change in storminess, judging by the figures for storms in North America, may mean an increase of 5 or 10 per cent; the change in temperature is only 0.6°C. This appears to represent the amount by which the direct and indirect loss of heat in the observed portions of the earth's surface by reason of the more rapid circulation exceeds the gain due to greater solar radiation. It is the result of many complex factors, including radiation, conduction, reflection, cyclonic storms, evaporation, rainfall, and local convection. All of these help to produce a lowering of the average temperature of the earth's surface. At the same time more rapid atmospheric circulation tends to cause more frequent variations and perhaps extremes of temperature. The process of diminishing the average temperature of the earth's surface by means of atmospheric movements takes place repeatedly before our eyes. It seems to explain "The Paradox of a Hot Sun and a Cool Earth."

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[9] C. G. Abbot: Note on the Theory of the Greenhouse, Phil. Mag., 6th Series, Vol. XVIII, 1909, p. 33.

[10] H. H. Clayton: World Weather, New York, 1923.

[11] S. S. Visher: Variability versus Uniformity in the Tropics, Sci. Mo., Vol. 15, 1922, pp. 23-35.

NOTE. Dr. Ernst Antevs has called my attention to the fact that as long ago as 1913 (Ann. Astrophys. Obs. Smiths. Inst., Vol. 3, p. 133) C. G. Abbot, F. E. Fowle, and L. B. Aldrich had made observations on the relative proportions of different wave lengths in the light at sunspot maxima and minima. In 1922 (Vol. 4, p. 206) they repeat their previous conclusion as follows: "High values of the solar constant are attended by a greater increase of energy in the shorter wave lengths than in the longer ones." This would be expected because the hottest stars are bluish. If short wave lengths are relatively abundant in the visible spectrum at times of high solar constants and of maximum sunspots, ultra-violet radiation is also presumably abundant. If this is true, the ozone hypothesis is untenable.

CHAPTER V

THE NATURE OF MODERN CLIMATIC VARIATIONS

THE next step in our investigation is to obtain a clearer picture of the general nature of the variations in weather which occur in the sunspot cycle. As a first step, let us compare the location of storminess in North America at times of sunspot minima and maxima. The American data cover four successive periods during which the number of storms in a three-year period of minimum spots may be compared with the number in a three-year period of maximum spots. The periods are as follows:

1. Minimum 1877, 1878, and 1879 vs. maximum 1882, 1883, and 1884
2. Minimum 1888, 1889, and 1890 vs. maximum 1892, 1893, and 1894
3. Minimum 1900, 1901, and 1902 vs. maximum 1905, 1906, and 1907
4. Minimum 1911, 1912, and 1913 vs. maximum 1916, 1917, and 1918

For all of these periods Kullmer has prepared maps showing the amount by which the storminess at times of maxima exceeded or fell short of the storminess at times of minima. Those for the last three periods are given in Figs. 10, 11, and 12. The map for the first period resembles the later ones and is given in *The Solar Hypothesis,* but is here omitted because of the scantiness of the data. In the maps the unshaded areas where figures occur mean that the three maximum years had more storms than the minimum years, while the shading means that storminess was deficient when the sunspots were at a maximum. Since the numbers represent periods of three years, they must be divided by three in order to obtain the average yearly departure of the maximum periods

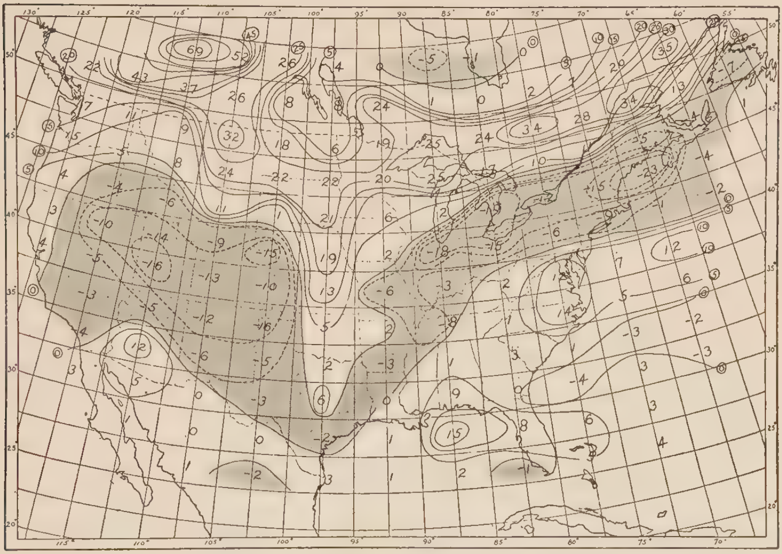

Fig. 10.

Storminess during the Sunspot Maximum of 1892-1894 compared with the Minimum of 1888-1890.

(*After Kullmer.*)

The unshaded areas (except the parts where there are no data) had more storms during the three years of maximum spots than during the three years of minimum spots. The shaded areas indicate more storms at sunspot minima than at maxima. The figures indicate the excess of storm centers crossing rectangles measuring 2½° north and south and 5° east and west during one of the three-year periods as compared with the other. The figure 32 in Montana, for example, means that 32 more storm centers crossed that region in the three years of *maximum* sunspots, 1892-1894, than in the three minimum years, 1888-1890. The figure —13 farther south in the shaded area in Colorado means 13 more storm centers in the *minimum* sunspot years.

from the minimum. Lines have been added at intervals of five to bring out the essential features. In Fig. 13 the three maps have been combined into a single map, showing the average difference between years of sunspot maxima and minima. Here the numbers indicate the average excess or deficiency of storm tracks per year and not for three-year groups, as in the other maps.

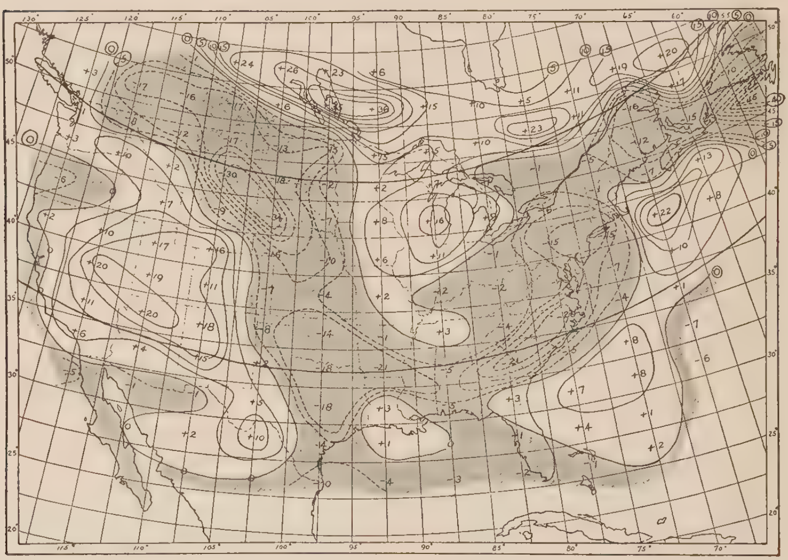

Fig. 11.

Storminess during the Sunspot Maximum of 1905-1907 compared with the Minimum of 1900-1902.

(*After Kullmer.*)

See description under Fig. 10.

The most striking fact about these maps is that all show the same general features. Although the location of the features varies somewhat from map to map, the variation is slight. The most noticeable features are as follows:

(1) A northern arc-shaped area of increased storminess during periods of many sunspots. This *boreal* belt lies along the southern border of Canada. It begins in latitude 55°N. on the west, drops down to about latitude 48° in the Great Lakes region, and then bends northeastward down the St. Lawrence Valley.

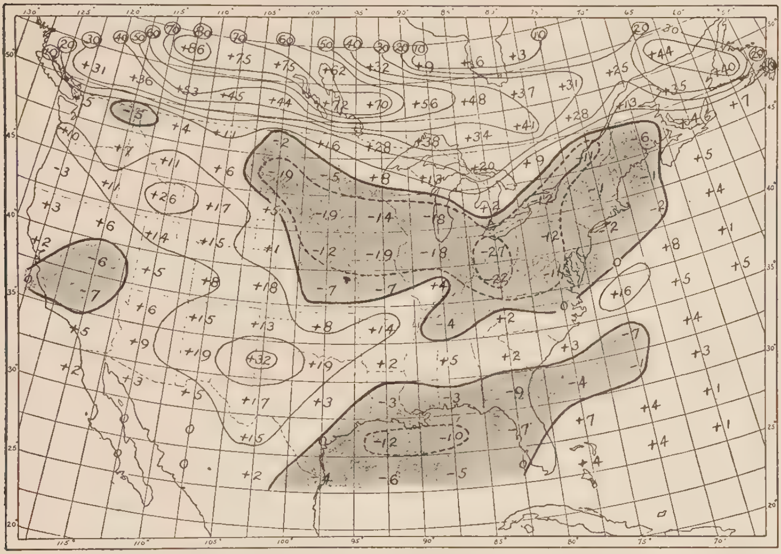

Fig. 12.

Storminess during Sunspot Maximum of 1916-1918 compared with the Minimum of 1911-1913.

(*After Kullmer.*)

See description under Fig. 10.

(2) On each of the maps an area of somewhat increased

storminess projects southward from the center of the boreal belt of increase. In Fig. 12, however, when the sun was most active, this almost disappears.

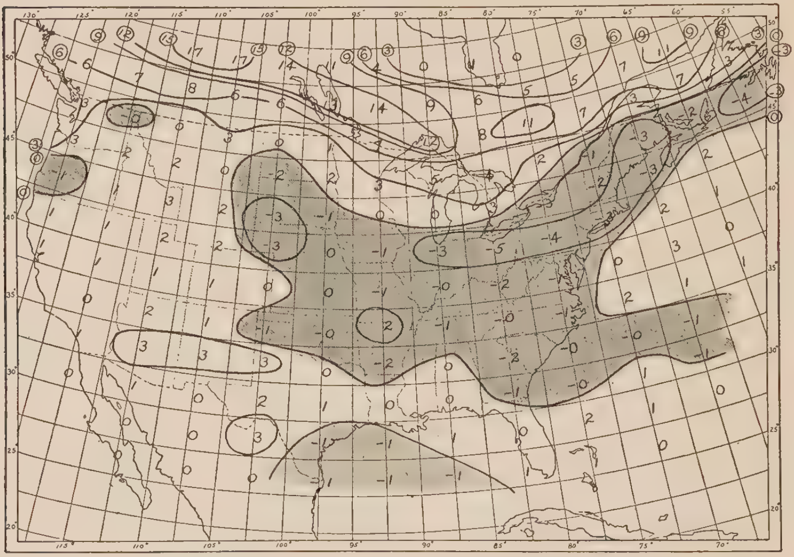

Fig. 13.

Storminess at Sunspot Maxima versus Minima.

(*After Kullmer.*)

This figure combines the data of Figs. 10, 11, and 12. It differs from those only in that instead of the *total* excess of storm centers in three-year periods of sunspot maxima compared with minima or the reverse, it gives the *average* excess per year when nine years of sunspot maxima are compared with nine years of minima. Unshaded areas (except where there are no data) had more storms at sunspot maxima, while shaded areas had more storms at sunspot minima.

(3) On either side of this projection, and almost divided by it into two parts in Figs. 10 and 11, lies a pronounced band of decreased storminess extending from

Oregon or Washington through the central United States to Nova Scotia.

(4) South of this we have a second area of increased storminess during times of many sunspots. Although slightly broken in Figs. 10 and 11, this *subtropical* belt forms a continuous band in Fig. 12, which appears to be the most typical because it represents the greatest solar activity and the period when our data are fullest. The subtropical belt is particularly well developed over the arid regions from California to western Texas, but also appears over the Atlantic Ocean.

The similarity of Figs. 10, 11, and 12 and of the partial map for an earlier period, not here reproduced, leads to the conclusion that we are dealing with a phenomenon which repeats itself regularly in every solar cycle. Not only the number but the location of storms seems to vary in harmony with solar activity. The shifting of storminess is so regular that we can scarcely avoid the conclusion that Kullmer has discovered one of the important laws of nature. Other investigators, such as Bigelow,[1] have noted a relation between sunspots on the one hand, and the location of storm tracks and the occurrence of cold waves on the other, but it has remained for Kullmer to frame a definite law of the shifting of storm tracks in harmony with solar activity.

Kullmer's law appears to be one aspect of a more general law which Clayton[2] has formulated as follows:

> It may be stated as a general law that in each cycle of change in solar activity, whether of long or short period, the effect in the temperate zone *begins* in high latitudes, progresses eastward and equatorwards with a velocity inversely proportional

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[1] Frank H. Bigelow: Studies on the Circulation of the Atmospheres of the Sun and of the Earth, Mo. Weath. Rev., 1903-1904.

[2] World Weather, 1923, p. 271.

to the length of the solar cycle, and *dies out* in low latitudes. The more intense the solar outbreak the higher the latitude in which the effect begins.

The nature of Kullmer's law can best be understood from Figs. 14 to 21, which show the actual number of storms in individual years and the amount by which the number of storms in each year exceeded or fell short of the average for the 30 years from 1883 to 1912, which Kullmer has taken as a fair representation of the average. The first year, 1911, was a typical period of slight solar activity. The average sunspot number was only 5.7. In the northern belt of main storminess, the number of storms was much below the average. Farther south in the central portion of the United States there was a decided excess of storms, while around the borders of the country there were fewer storms than usual. The year 1911, as Arctowski[3] has shown, was characterized by what he calls a thermopleion, that is by an excess of temperature in most parts of the world. As he puts it:

> An abnormal increase of temperature during the latter part of 1911 and in 1912 is a striking feature of the curves of meteorological stations in Alaska, British Columbia, Vancouver Island, Oregon, and, to a certain extent, California: then of Mexico, Panama, the West Indies, the Bahamas, British and French Guiana, Matto Grosso, Parana, Peru; the Faroe Islands, Holland, northern Germany, Switzerland, Italy, Gibraltar, Algeria, Morocco, the Canary Islands; the Sahara, Egypt; Senegambia, the French Congo, the Transvaal; Aden, Quetta, India, Ceylon, Mauritius, and the Seychelles Islands; the Straits Settlements, Cochin China, China, Japan, eastern Siberia; Australia and the Touamotou Islands in the Pacific.
>
> The records of a certain number of stations show a retarded pleionian effect. I will cite those of Greenland, Iceland, Carolina,

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[3] H. Arctowski: The Pleionian Cycle of Climatic Fluctuations, Proc. 2d Pan-American Scientific Congress, 1915-1916, Vol. 2, pp. 172-178.

Florida, Cuba, the Caucasus and Russia, southern Nigeria, Togo, German South Africa, Madagascar, Palestine, Mesopotamia, some stations in India, Christmas Island, the Philippines, and New Caledonia. Even in the Antarctic regions the records of Cape Evans station, under 77° 38′ south latitude, show that during the months of May to September, or during the South Polar winter, the mean temperature of 1912 was 10°F. higher than in 1911.

In striking contrast with these results, most stations in the United States, as well as Wellington and Auckland in New Zealand, and some stations in Russia, show a well-pronounced depression of temperature corresponding in time with the occurrence of the hormopleion [that is, the general wave of meteorological conditions] and the greatest development of the thermopleionian [warm] conditions in so many countries in different parts of the world.

The American antipleion [or area of low temperature] is of particular interest because of the pleions observed in the Northwestern States, Alaska, Canada, and Greenland, as well as in the Southeastern States, the West Indies, and Mexico. In North America temperature conditions were evidently in conformity with the hormopleion, except in the greatest part of the central portion of the continent. Moreover, it was precisely at the time of occurrence of the hormopleionian maximum, or soon afterwards, that the greatest lowering of temperature was observed in the Middle West from North Dakota down to Texas.

I have quoted from Arctowski at considerable length because his wholly independent researches dovetail into Kullmer's so neatly. The years 1911, 1912, and 1913 were times of few sunspots, the numbers being 5.7, 3.6, and 1.4. Hence, according to our interpretation, storminess was rare. The solar constant was not at its lowest, but was not so high as at times of greatest solar activity. Because of the absence of storms, however, the sun was able to warm most parts of the earth to an unusual degree. Only in a few regions did it fail to do this. The greatest of those regions, the central United States, is a chief region where storminess increases at times of few sunspots, for with every change in solar activity the places of chief

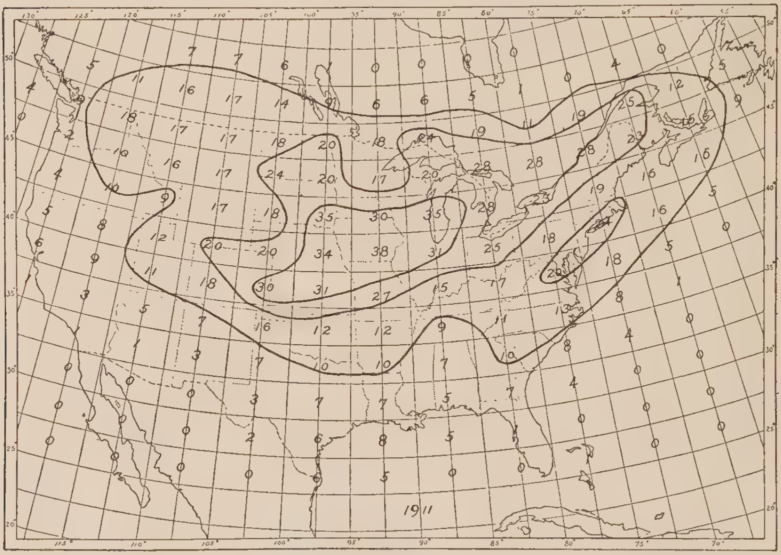

Fig. 14.

Total Number of Storm Tracks in 1911.

(*After Kullmer.*)

The figures indicate the number of storm centers crossing rectangles 2½° north and south and 5° east and west.

storminess also change their positions. Presumably the same was true in New Zealand and in parts of Russia, although no data are available. In other words, we have here a concrete example of the paradox which was discussed in the last chapter. There we saw that during years of abundant storms the earth as a whole is relatively cool.

Here we see that even when the earth as a whole was warm, a great area where storms were unusually abundant was cool.

Let us turn back now to the maps of storminess in the United States. The one for 1912 is omitted because it is midway between those for 1911 (Figs. 14 and 15) and 1913 (Figs. 16 and 17). The maps for 1913 are remarkable chiefly by way of contrast to those of 1914 (Figs. 18 and 19). The change is almost kaleidoscopic. In Fig. 19 for

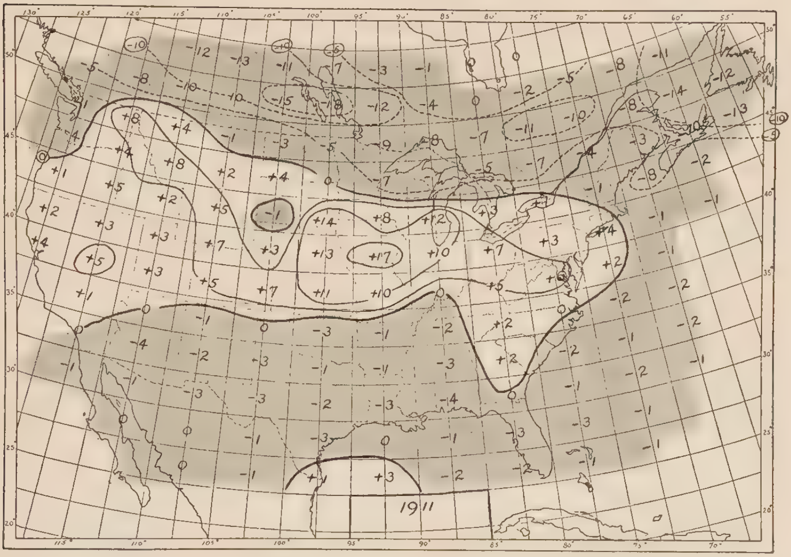

Fig. 15.

Departures of Storminess in 1911 from Average of Thirty Years, 1883-1912.
(*After Kullmer.*)

The numbers in the unshaded areas indicate the excess of storms in 1911 compared with the thirty-year average. The numbers in the shaded areas indicate a corresponding deficiency.

1914, the main features of Fig. 17 for 1913 are still visible, but have been crowded to the south by a new feature,—a marked increase in storminess in the boreal belt in southern Canada. The year 1914 had a sunspot number of only 9.6, but apparently it marked the beginning of a new order. Something, whether it be terrestrial or solar, seems suddenly to have started a new series of storms. In some places in the boreal belt the number almost doubled. At the bottom of Fig. 19 an old series of storms seems to be finally disappearing. The year 1915, for which the map is not reproduced, is much like 1914 except that the

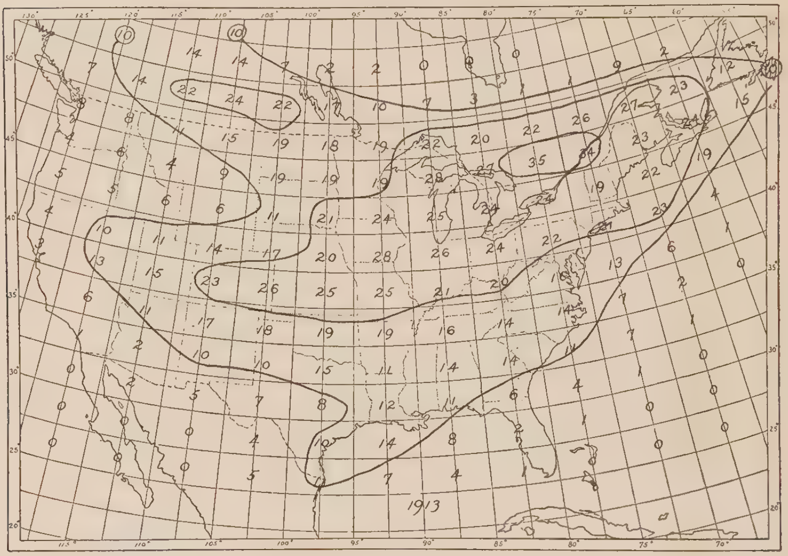

Fig. 16.

Total Number of Storm Tracks in 1913.

(*After Kullmer.*)

See description under Fig. 14.

southern series of storms, which we have called the old series, has disappeared. Sunspots were then rapidly increasing, for the average for the year rises to 47.4. The next year the sunspot number was 55.4 and all the features of the preceding map still appear, with the addition of a small area of diminution in the South near the Gulf of Mexico. In 1917 the sunspot number rose to 103.9, the highest since 1871. That year, as appears in Fig. 21, the belt of increased storminess in the North reached its most northern latitude. The area of diminished storminess in

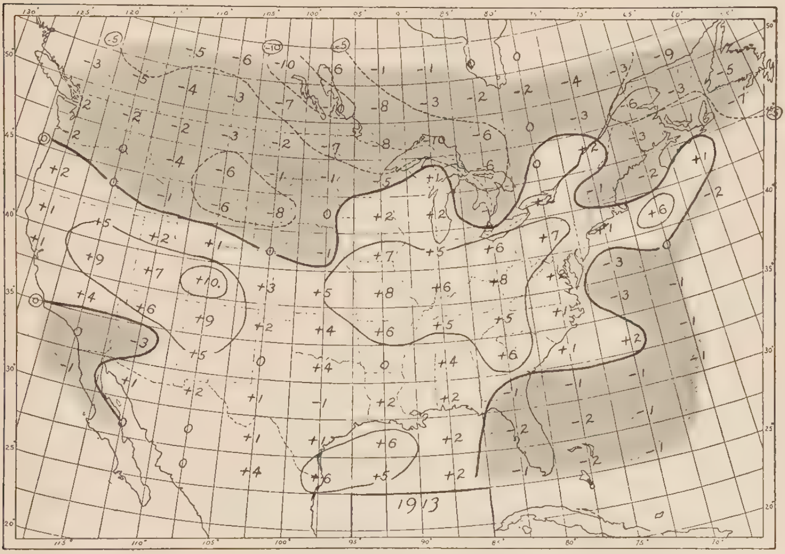

Fig. 17.

Departures of Storminess in 1913 from Average of Thirty Years, 1883-1912.

(*After Kullmer.*)

See description under Fig. 15.

the interior of the United States also lay far north and was reduced to small portions. Farther south the area of increased storminess was still distinct in the Southwest and along the Atlantic coast, but was most highly developed in the Mississippi Valley. Far to the south in this year of most abundant sunspots there was a well-marked area of diminished storminess near the Gulf of Mexico and extending eastward and northward in the Atlantic Ocean and westward and northward along the Pacific coast. Since the amount of storminess for these border regions is always slight, the percentage of decrease from

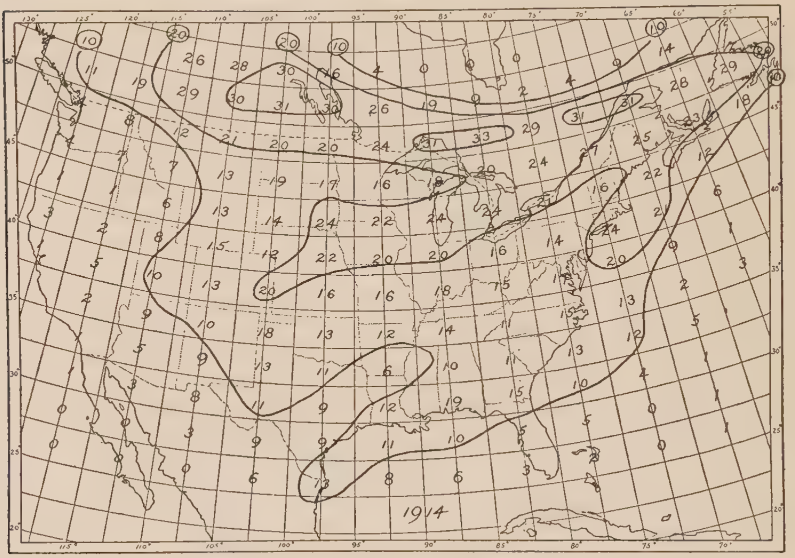

Fig. 18.

Total Number of Storm Tracks in 1914.

(*After Kullmer.*)

See description under Fig. 14.

California around through Mexico and the Gulf of Mexico to the Atlantic is surprisingly large. The year 1918, when the sunspot number was 80.6, shows the beginning of a return toward the conditions which prevail when sunspots

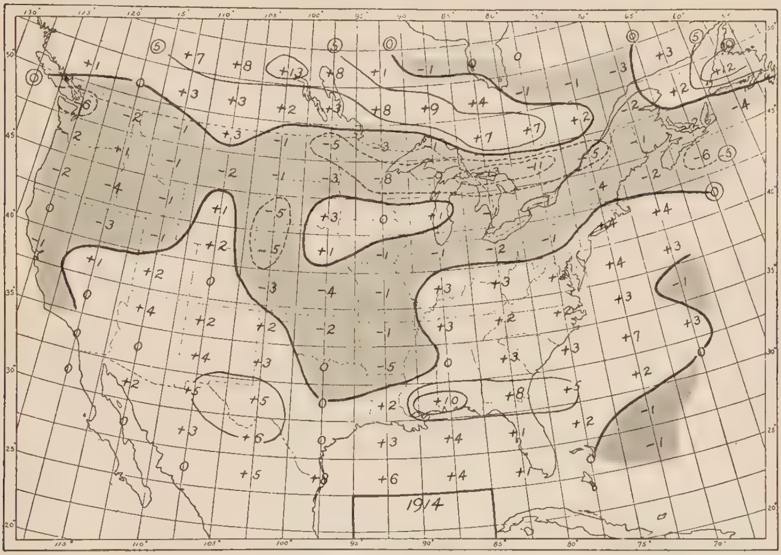

Fig. 19.

Departures of Storminess in 1914 from Average of Thirty Years, 1883-1912.

(*After Kullmer.*)

See description under Fig. 15.

are scarce. Judging by previous sunspot cycles and by what has happened up to the date of writing, the belt of unusual storminess which lay in southern Canada at the sunspot maximum will move gradually south, pressing the other belts before it until with the next sunspot minimum we shall presumably have a return to conditions like those of Figs. 15 and 17.

This gradual migration of the belts of storminess from north to south is a highly striking phenomenon which repeats itself with every sunspot cycle. It forms the basis of Kullmer's generalization as to the shifting of storm tracks. The generalization may be tentatively stated as follows: When a new sunspot cycle is inaugurated, a sudden change causes a great increase in storminess in the northern belt. The intensity of this belt continues to increase so long as solar activity increases. Not only does storminess increase in this belt, but the belt shifts progressively northward. After the time of maximum stormi-

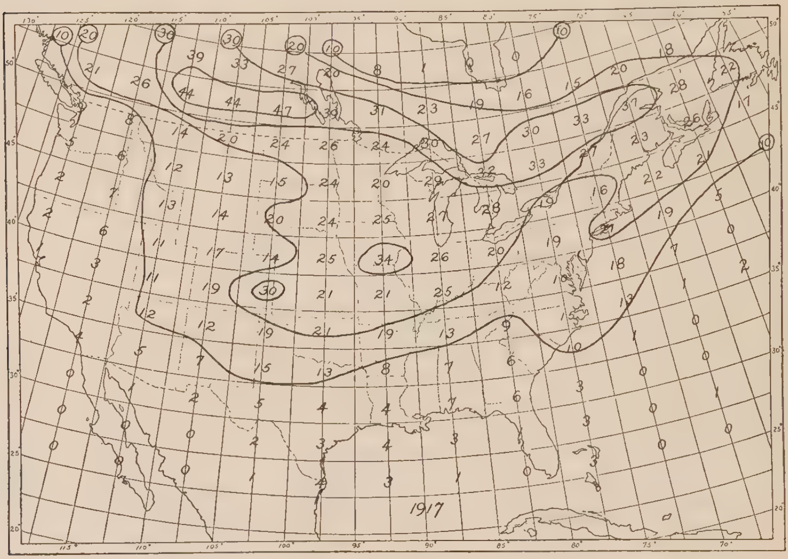

Fig. 20.

Total Number of Storm Tracks in 1917.

(*After Kullmer.*)

See description under Fig. 14.

ness has passed and the northernmost location of the storm belt has been reached, the belt of excessive storminess gradually shifts southward, so that when sunspots are scarce it lies over the center of the United States.

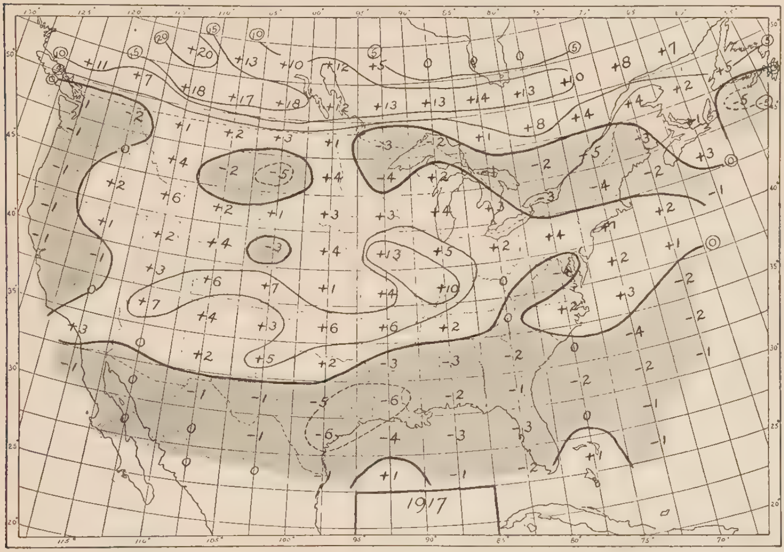

Fig. 21.

Departures of Storminess in 1917 from Average of Thirty Years, 1883-1912. (*After Kullmer.*)

See description under Fig. 15.

Finally, when a new cycle of sunspots begins, the old series of storms and the new series are both visible, as in Fig. 19, one lying in about latitude 30° and the other north of 50°.

In Europe the evidence as to a relation between the sun and the weather is not so clear as in the United States, because the records are not so homogeneous over a large

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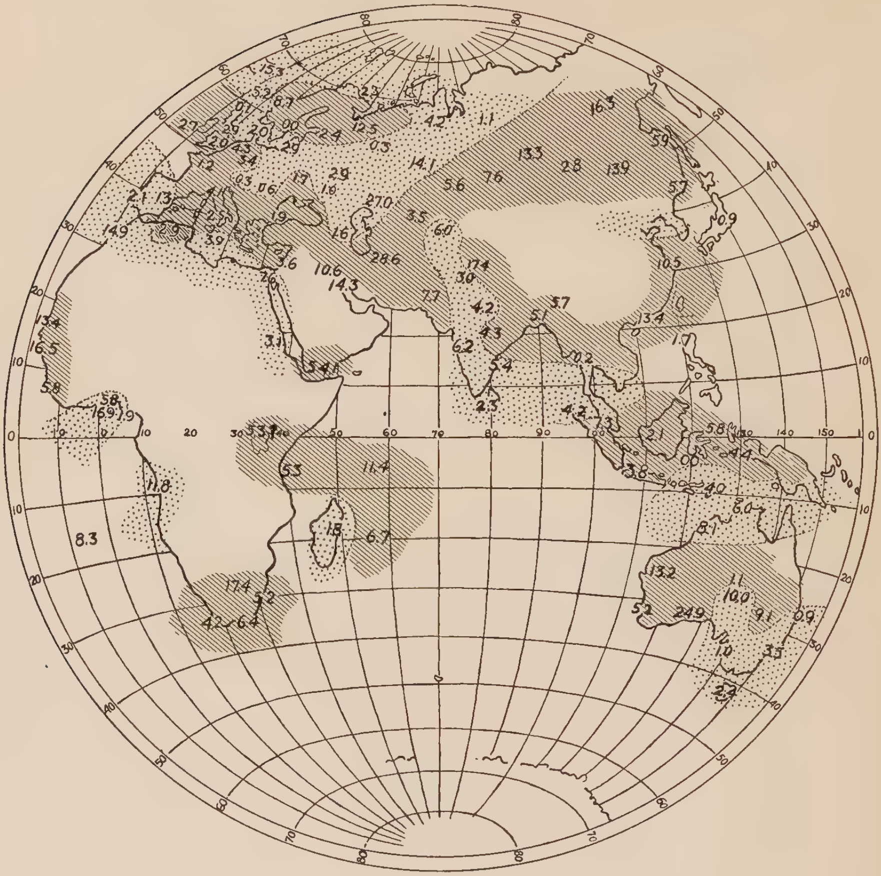
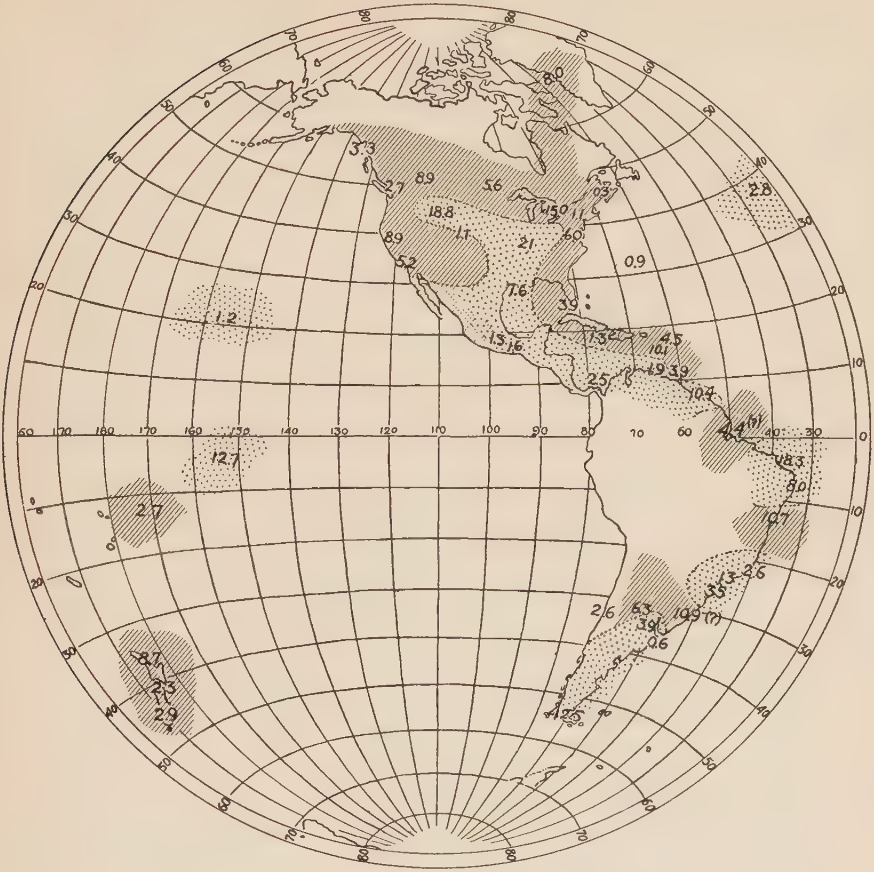


Fig. 22.

Relative Rainfall at Times of Increasing and Decreasing Sunspots.

Heavy shading, more rain with increasing spots. Light shading, more rain with decreasing spots. No data for unshaded areas.

Figures indicate percentages of the average rainfall by which the rainfall during periods of increasing spots exceeds or falls short of rainfall during periods of decreasing spots. The excess or deficiency is stated in percentages of the average. Rainfall data from Walker: Sunspots and Rainfall.



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area. Nevertheless, as far as it goes the evidence points to the same type of relation as in America. We have already seen that Douglass' measurements of tree growth for a hundred years suggest that when sunspots are numerous, storms in Germany are abundant in summer, but scarce in winter. In order to test the matter in another way I have prepared Fig. 22, which includes not only Europe but the whole world. It is based on the tables of annual rainfall given by Walker[4] for about 150 stations distributed as widely as possible, and covering periods ranging from 16 to over 100 years, but mostly from 35 to 60. The sunspot cycle has been divided as follows:

A. Years of sunspot maximum.
B. One year after maximum.
C. Two years after maximum.
D. Three years after maximum.
E. Intermediate period of varying length.
F. Two years before minimum.
G. One year before minimum.
H. Minimum.
I. One year after minimum.
J. Intermediate period of varying length.
K. One year before maximum.

Instead of using years of maximum and minimum sunspots, as in the preceding comparison, I have used periods of increase and decrease, for Kullmer's maps, Figs. 14-21 and others, suggest that this is the most important contrast. Because of the evidences of both solar and terrestrial activity at times of sunspot minima, as already explained, I have assumed that a new period in the total solar activity begins just before the apparent minimum.[5]

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[4] G. T. Walker: Sunspots and Rainfall, Mem. Ind. Meteor. Dept., Vol. XXI, Pt. x, 1915.

[5] Extra weight has been given to the intermediate years when the spottedness is manifestly increasing or decreasing. This appears from the following

Later study may show that a slightly different arrangement would be better, and longer and more abundant records will certainly change the details of Fig. 22, as well as fill out its blank spaces. Yet as the map stands it represents the best available data as to how the rainfall varies between the times when solar activity is on the increase and on the decrease. The heavy shading indicates that rainfall, and presumably storminess, increase during times of increasing solar activity. The light shading points to the conclusion that storminess decreases at such times in these areas. In Europe, areas of increasing rainfall in Scandinavia and the Mediterranean region correspond to similarly placed areas in Canada and the Southwest. In the interior of Europe and northern Asia, an area where rainfall decreases corresponds roughly with a similar area in the interior of the United States. Perhaps the most surprising feature of the map is the almost uniform decrease in rainfall along the heat equator at times of solar activity. The meaning of this is discussed in *Climatic Changes*. Meanwhile, Fig. 22 confirms our previous conclusion that the earth's surface is somewhat intricately divided into areas which respond to solar activity in opposite ways.

Although much still remains to be done before the whole matter is finally settled, the general nature of the contrast between times of maximum and minimum solar activity seems fairly clear. When the sun is active the con-

statement of the years used in the periods of increasing and decreasing sunspots and of the weight attached to each:

Increasing spots: G+2H+3I+3J+2K+A
Decreasing spots: B+2C+3D+3E+2F+G

Because the sunspot cycle consists of an odd number of years, 11, and cannot be divided equally, it has been necessary either to omit one year or to use it twice. I have chosen to use G, two years before minimum, twice, because there is evidence that at that time the solar constant and other related phenomena begin to change as if a new cycle were being inaugurated.

trast between areas of high and low pressure is accentuated. In winter, after the semipermanent high pressure areas over North America and Eurasia become well established, cold clear weather prevails more steadily than usual and storms are relatively scarce in the central parts. In North America this central strip extends from Manitoba across the Great Lakes to the Maritime Provinces, as appears in Fig. 23, which shows the excess or deficiency of storminess at times of sunspot maxima versus minima

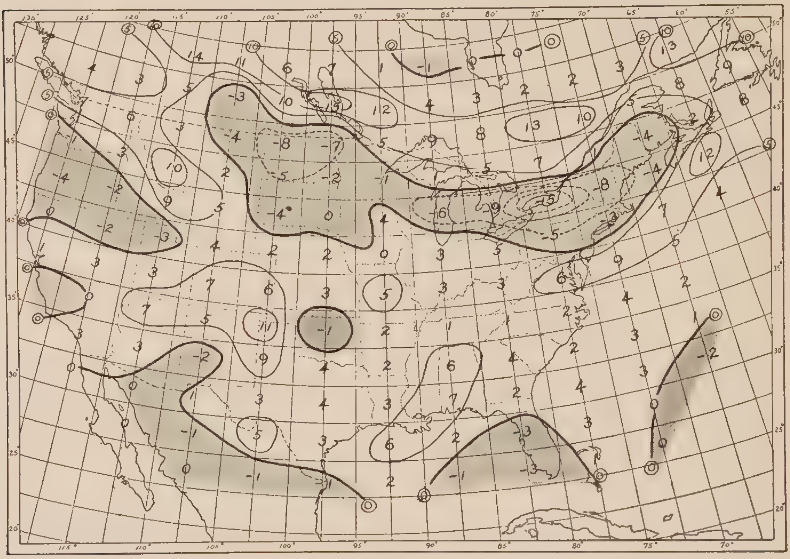

Fig. 23.

Storminess in January at Sunspot Maxima versus Minima.

(*After Kullmer.*)

Same as Fig. 13 except that the month replaces the year, and the figures indicate *total* excess of storms at maxima (unshaded) or minima (shaded) instead of yearly averages.

in January. Outside this central area, however, the number of storms generally increases at times of sunspot maxima, although in the south and over the oceans this tendency disappears. From midwinter onward an excess

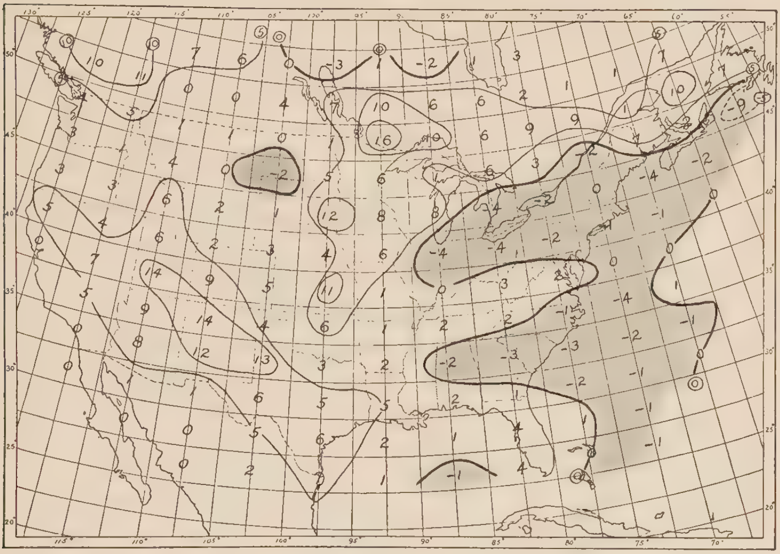

Fig. 24.

Storminess in May at Sunspot Maxima versus Minima.

(*After Kullmer.*)

See description under Fig. 23

of storminess at times of sunspot maxima becomes more and more pronounced. It culminates in May, Fig. 24, when almost all parts of the United States, except the Atlantic coast, are unusually stormy. This is peculiarly important in the Southwest, because it causes storms and rain at a time when they are especially important to agriculture.

In summer, on the contrary, at times of many sunspots storminess decreases over most of the United States, although there is a systematic increase in all the border regions, including the Pacific coast, Canada, the Atlantic, and Mexico, as appears in Fig. 25, representing August. As the autumn advances, Fig. 26, these peripheral areas of increased storminess press inward, a fact which is of special importance in the arid Southwest where it means a relative abundance of rain in the autumn when the winter crops are sown. A fuller analysis of the variations

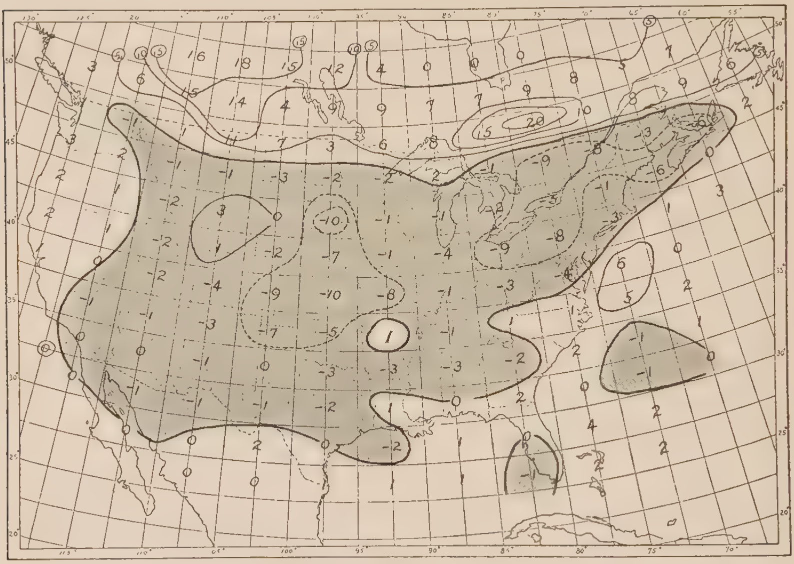

Fig. 25.

Storminess in August at Sunspot Maxima versus Minima.

(*After Kullmer.*)

See description under Fig. 23.

in solar responses according to both the season of the year and the geographical location is one of the most interesting and profitable tasks that now confronts the meteorologist.[6] So far as it has yet been attempted it suggests a distinct agreement between the distribution and variations of storminess in the Old World and the New.

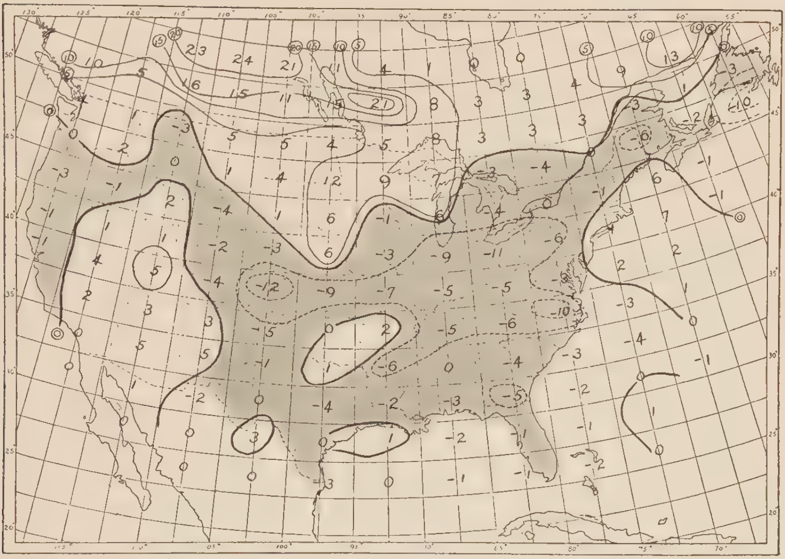

Fig. 26.

Storminess in November at Sunspot Maxima versus Minima.

(*After Kullmer.*)

See description under Fig. 23.

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[6] H. Arctowski: Mo. Weath. Rev., August, 1915, p. 385.
Ellsworth Huntington: Proc. Second Pan-American Scientific Congress, 1915-1916, Vol. 2, pp. 411-431.

CHAPTER VI

ELECTRICAL ACTIVITIES OF THE SUN AND EARTH

THE suddenness and irregularity of many changes of the weather, their simultaneous occurrence in remote and seemingly unconnected places, and the difficulty of explaining them on the basis of temperature alone has led to much speculation as to other possible causes. Naturally an electrical cause has been appealed to by many investigators. Tice[1] in 1875 was one of the first to discuss an electrical cause of the weather. Toward the end of the last century Veeder[2] published a most suggestive, although by no means complete, sketch of a similar electrical hypothesis. Helland-Hansen, Bigelow, and Kullmer, as well as various other students, have also published suggestions along this line, but no one seems to have gone into it thoroughly. This chapter is devoted to a statement of what is actually known as to the electrical relations of the earth and the sun, while the next three are devoted to an attempt to determine whether there is really any ground for an electrical hypothesis of the weather.

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[1] Tice, John H.: Elements of Meteorology, St. Louis, 1875.

[2] M. A. Veeder: numerous articles chiefly in the Proceedings of the Rochester Academy of Sciences, 1886 to 1896. A sketch of his life, a résumé of his work with references, and one of his unpublished manuscripts appeared in the Geographical Review, Vol. 3, 1917, pp. 188-211, and 303-316, under the title "The Geographical Work of Dr. M. A. Veeder." Dr. Veeder appears to have been a man of great originality and industry who might have advanced the science of meteorology conspicuously if he could have devoted his whole time to it. If it should ultimately be found that any important portion of the earth's weather is due to the electrical activity of the sun, the name of Veeder will deserve a highly honorable place in science.

The evidence of some kind of electrical or magnetic connection between the sun and the earth seems conclusive. The best-known evidence is perhaps the close correspondence between solar disturbances and perturbations of the magnetic needle. This relationship appears to be so well established and so widely accepted that it is unnecessary to discuss it in detail. It is illustrated in Fig. 27, where Bauer[3] compares the annual values of changes in magnetic energy with corresponding values of solar energy as measured in three different ways. The upper curve shows the solar energy as measured in the usual way by Wolfer's sunspot numbers. In the second curve Bauer uses the month as the unit and computes the average departure of the daily sunspot numbers from their mean for the month, regardless of sign. The degree to which this method of measuring the sun's activity causes the curves thus derived to agree with various curves of magnetic and electrical energy upon the earth leads Bauer to believe that "it is the variability in sun-spottedness, rather than sun-spottedness itself, which may approximate to a true measure of the kind of solar activity which may be related to geophysical phenomena." This conclusion agrees essentially with that to which we have been led by a study of the solar relationships of the weather.

The third curve in Fig. 27 is based on Bauer's summation of the magnetic energy of the whole earth. He bases this on the average horizontal intensity of terrestrial

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[3] L. A. Bauer: Measures of the Electric and Magnetic Activity of the Sun and the Earth, and Interrelations; Terrestrial Magnetism and Atmospheric Electricity, March and June, 1921, pp. 33-68.

The journal here referred to contains a large number of valuable articles relating to the general subject of the relation between the electrical and magnetic conditions of the earth and the sun.

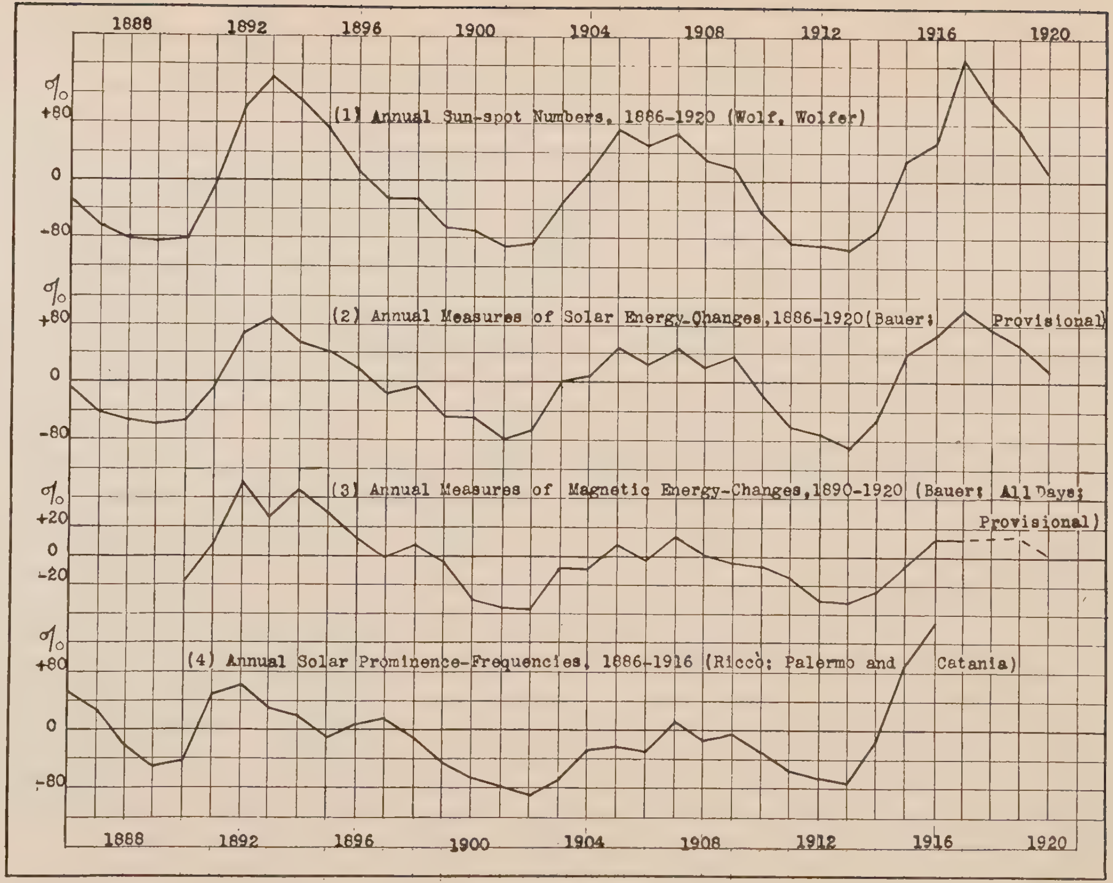

Fig. 27.

Variations in Solar and Magnetic Activity, 1886-1920.
(*After Bauer.*)

(*Courtesy of Department of Terrestrial Magnetism, Carnegie Institution of Washington.*)

magnetism for each month modified by the average diurnal range of the same condition, that is, by the average difference between the maximum and the minimum for each day. The fourth curve shows solar activity as measured by the frequency of the solar prominences observed at Palermo and Catania in Italy. The general agreement of all four curves is obvious. The greatest discrepancy between the magnetic curve and the solar curves occurred in 1894, but even in that year the solar prominences show a suppressed maximum corresponding to the more pronounced maximum of the magnetic curve.

Another interesting line of evidence is found in observations of magnetic phenomena during solar eclipses.

> Briefly stated, the general result has been that an appreciable magnetic effect, though of a minute order, is recorded during the period of a solar eclipse, similar in character to the variation experienced by the earth during a solar day, and differing from it only in magnitude.[4]

If so small a matter as an eclipse can produce an appreciable effect by cutting off the sun's magnetic influence, it seems clear that the sun's total effect must be important.

Other evidence collected by scores of investigators lends much support to Bauer's statement that

> it would appear at times as though the magnetic curve may be a more faithful index of the sun's complete activity or energy, at least with respect to . . . radiations and emanations which are likely to have an effect upon the earth's magnetic and electrical conditions, than the sunspot numbers themselves. In fact the various measures of solar activity differ as much among themselves . . . as the magnetic curve differs from any particular solar measure.

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[4] L. A. Bauer: Some of the Chief Problems in Terrestrial Magnetism and Electricity, Proc. Nat. Acad. Sci., Oct., 1920, Vol. 6, pp. 572-580.

Auroras are another electrical phenomenon closely connected with magnetism and with the sun.

> That there is an intimate connection between auroras when visible in temperate latitudes and terrestrial magnetism is scarcely open to doubt. A bright aurora visible over a large part of Europe seems always accompanied by a magnetic storm and earth currents, and the largest magnetic storms and the most conspicuous displays have occurred simultaneously.[5]

Abundant observations prove that auroras are connected with solar disturbances quite as closely as with magnetic disturbances. An example of this is given in Table 17, based on auroras visible in Scandinavia from 1749 to 1877, as given by Chree in Britannica. These years have been divided into groups of twelve, or in two cases eleven, years on the basis of the number of sunspots each

TABLE 17

AURORAS AND SUNSPOTS

A	*B*	*C*	*D*
Number of years	*Sunspot numbers*	*Total auroras seen in Scandinavia*	*Average number of auroras per year*
12	0.0 to 6.8	350	29.9
12	7.0 to 11.3	700	59.8
12	12.2 to 16.6	738	61.5
12	17.1 to 28.1	765	63.8
11	30.0 to 36.8	812	73.8
12	37.3 to 45.0	983	81.9
12	45.0 to 54.2	995	82.9
12	54.8 to 66.5	1024	85.3
12	66.5 to 83.4	1279	106.6
11	84.8 to 101.7	1241	112.8
12	103.2 to 154.4	1390	115.8

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[5] C. Chree: Encyclopedia Britannica; article ''Aurora.''

year. For instance, the first group includes twelve years having sunspot numbers ranging from 0 to 6.8. The next group contains the twelve years with the next higher spot numbers, from 7.0 to 11.3. The auroral data show the number of auroras seen in Scandinavia. As the sunspot numbers increase, the auroras also increase with almost perfect regularity. There is only one chance in forty million that the eleven numbers in column D would accidentally arrange themselves in the same order as those of column B.

Earth currents are a third electrical phenomenon which cannot be ignored in this connection. Unfortunately the longest record yet available is that of the Observatory of Ebro in Spain, and even that dates only from 1910. The study of this record by Bauer[6] seems to show that the earth currents respond to the same general cosmic or solar control as magnetism and auroras. The strength of the earth currents is measured by the potential gradients in the direction of the normal flow of the currents from the general region of the northern magnetic pole toward the south-southeast. During the period from 1910 to 1920, inclusive, these gradients reached their lowest value in 1918, or a year after the sunspot maximum. This seems to Bauer to confirm certain other evidence of a lag in the earth currents as well as in the frequency of auroras after their supposed solar cause. Bauer's main conclusion is that the earth's magnetic energy, the average intensity of its magnetization, and the strength of the normal electric currents circulating in the earth's crust all suffer a diminution during increased solar activity. On the other hand the *variability* of all these manifestations of energy, that is, their range from maximum to minimum during a given unit of time, increases in harmony with solar activity. Bauer interprets the diminution of the earth currents as meaning that when the sun is active it sets up currents in a direction reverse to that of the normal currents. It is interesting to speculate what would happen if this reversal of earth currents and the accompanying diminution of the earth's magnetization should proceed to great lengths under the influence of extreme solar disturbances. Would the ultimate result be a reversal in the signs of the two poles, followed by a new magnetization in which the South Pole would act as the North Pole now acts? In the sun, as we shall see later, there is evidence of a remarkable reversal of the electrical signs of sunspots at certain times. It is not yet known how far-reaching this is, but it has not reversed the polarity of the sun since observations have been made.

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[6] L. A. Bauer: Some Results of Recent Earth-Current Observations and Relations with Solar Activity, Terrestrial Magnetism, and Atmospheric Electricity; Terrestrial Magnetism and Atmospheric Electricity, March-June, 1922, pp. 1-34.

From the climatic standpoint atmospheric electricity is presumably more important than magnetism, auroras, or earth currents. These four electro-magnetic phenomena appear to be so closely interrelated that it is almost impossible to discuss the causes of one without considering the causes of the others. Before inquiring into the solar relationships of these four types of phenomena, however, let us briefly see what is known of atmospheric electricity, even though our knowledge is as yet highly imperfect. The earth's surface is, in general, negatively charged. The lower air, on the contrary, is usually either positively charged or has only a weak negative charge. Hence there is normally a positive gradient from the earth to the air. But as Humphreys puts it,

> The vertical gradient near the surface of the earth varies greatly, with location, season, hour, and weather conditions—occasionally even reversing sign during storms—but the general

> average over level areas and during fine weather appears to be of the order of 100 volts per meter.[7]

The gradient increases in general with latitude, or at least from the equator as far as temperate latitudes. There it is high in winter and low in summer. The gradient also varies in a diurnal period, being in general low at night and high by day. Since

> fog, rain, and other forms of precipitation are nearly always electrically charged [they] often greatly modify and occasionally reverse the potential gradient as do also heavily charged or thunder clouds. Cirrus and other types of high fair-weather clouds produce little or no effect. (Humphreys.)

The number of ions, or charged particles, in the air is the main determinant of atmospheric conductivity, and has a large effect on the potential gradient. This number, as Humphreys says,

> varies greatly, being very small during foggy and dusty weather (for then nearly all the ions are attached to masses so large that their velocity is small), and relatively large when the air is clear. In general it is larger during summer than winter, larger during the daytime than at night, and larger when the temperature is high than when it is low. It also increases with elevation through at least the first few kilometers, but to what maximum value is not known.

In balloon ascents up to 9.5 kilometers Kolhörster found that the ionization increased tenfold. Swann believes that

> the rate at which the apparent ionization increases with altitude in the neighborhood of 9 kilometers is such as to suggest that at altitudes but slightly greater, the ionization might attain enormous values. The validity of Kolhörster's results has been questioned by C. H. Kunsman in view of possible complications re-

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[7] W. J. Humphreys: Physics of the Air, 1920, p. 409.

sulting from the effect of low temperature on the insulating material used; if, however, they should be substantiated, they afford one of the most convincing evidences that one could wish as to the true cosmic nature of part at least of the so-called penetrating radiation.[8]

In a general way, and in spite of frequent exceptions, it may be said that whenever and wherever the sun's influence is great the number of ions in the air is also great. As a rule the number of ions in the lower atmosphere is of the order of 800 positive and 680 negative per cubic centimeter. At high altitudes the number is far greater, as is the conductivity, which at an elevation of 6 kilometers may be roughly 20 times as great as at the earth's surface. The velocity of the ions varies inversely as the atmospheric pressure, so that it increases in the upper air.

The number of ions brought down by rain and snow has been the subject of a most accurate and conclusive investigation by Simpson.[9] He found that during thunderstorms the rain brings down both positive and negative ions, but the total quantity of positive electricity thus brought to the earth is 3.2 times as great as the negative. With snow the same is true, the ratio in Simpson's experiments being 3.6. The more rapid the fall of rain and the larger the drops the greater the proportion of positive ions. While rain is falling the potential gradient is more often negative than positive, but this apparently has no relation to the sign of the charge on the drops. If the charges on the raindrops and snowflakes be treated as equivalent to electrical currents, the current densities found by Simpson were generally smaller than 4×10^{-15}

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[8] W. F. G. Swann: The Penetrating Radiation and Its Bearing upon the Earth's Electric Field, Bull. Nat. Res. Coun., No. 17, 1922, pp. 65-73.

[9] G. C. Simpson: Memoirs, Indian Meteorological Survey, 1910, Vol. 20, Pt. 8. Also Phil. Mag., Vol. 30, 1915.

amperes per square centimeter, but occasionally both negative and positive currents were decidedly stronger. Positive currents, as already implied, were more numerous than negative, and the general strength of the currents in snowstorms was greater than in thundershowers.

Simpson's explanation of the excess of positive over negative charges in rain and snow depends on his own experiments. On allowing drops of distilled water to fall through an upward blast of air strong enough to produce spray, both positive and negative ions were set free, the ratio being one positive for three negative. This is the reverse of the condition in rain and snow. It seems to mean that when rain falls, it is blown about more or less by the wind and broken into spray. Its electrical charge is thereby broken up and released. The negative ions, in the ratio of three out of four, escape into the air and increase its negative charge, while the positive ions are carried to the earth by the rain and temporarily may reverse the usual negative charge of the earth's surface.

One result of this breaking up of the electrical charges of the clouds is that in the lower part of a thundercloud where the drops are beginning to fall, and to a less extent presumably in other clouds, the cloud is positively charged, while the upper part of the same cloud is negatively charged, because the negative ions have stayed there. Since the earth is normally negative in its charge, we thus have a positively charged layer between two negatively charged layers. This condition gives rise to the electrical discharges which are known as lightning. It tends to be destroyed by the lightning and also by the rain, which carries the positive ions down to a level where they can unite with the negative ions near the earth's surface and thus be neutralized.

The degree of electrification produced in thunderclouds offers a most perplexing problem. As Humphreys puts it,

> Judging from the voltages required to produce laboratory sparks, roughly 30,000 volts per centimeter, it is not obvious how such tremendous potential differences can be established between clouds or between a cloud and the earth as would seem to be necessary to produce a discharge kilometers in length, as often occurs. Indeed, a fatal objection to the assumption of such high voltage is the effect it would have on the velocity of fall and consequent size of electrified raindrops. According to Simpson, thunderstorm rain often carries as much as 6 electrostatic units of electricity per c.c., and occasionally even more. Hence 30,000 volts per centimeter would produce an electric force on such rain roughly six-tenths that due to gravity and therefore either retard its fall, if directed upward, or, if directed downward, give it a velocity that would quickly break it into smaller drops. But thunderstorm rain does not consist essentially of smaller drops. On the contrary, as casual observation leads one to believe and as measurements have shown, raindrops average larger (1 to 6 mm. in diameter) during a thunderstorm than at any other time. Their velocity of fall therefore cannot be excessive, nor indeed does it ever appear to be greatly different from that of ordinary rain. Hence electrical gradients of the order above assumed do not exist between clouds and the earth. . . . At present, therefore, one can do but little more than speculate on the subject of the primary lightning discharge, but even that much may be worth while since it helps one to remember the facts.

The conditions described above give rise to three more or less permanent shells: First, the negatively charged surface of the earth; then the positively charged lower atmosphere, which sometimes has a very weak negative charge, and, third, the negatively charged upper atmosphere. One result of the shells appears to be that when a wireless message is sent out the energy acting upon the receiving apparatus is greater than would be expected.

Apparently the wireless waves do not radiate outward in all directions alike. In the first place, they travel around the earth rather than through it, since it is a charged conductor. When this is allowed for, however, there is still a surplus of energy at the receiving station. Hence, in the second place, the waves appear to be prevented from radiating freely outward. For this reason, even if there were no other, physicists would conclude that the upper air must also be a charged conductor and that it prevents wireless waves from escaping. The fact that the outer shell remains constantly electrified in spite of continual leakage is almost impossible to explain unless the charge is maintained by some outside source, such as the sun.

Certain other phenomena of atmospheric electricity likewise seem explicable only on the assumption of a supply of energy from some outside source. One of these is the steady conduction currents. These differ not only from the precipitation currents already mentioned, but from lightning and the irregular mechanical currents due to the wind and to ordinary movements of the air in convection. The conduction currents, as Humphreys puts it, are

> due to the downward flow of one set of ions, usually the positive, and the simultaneous upward flow of the other in response to the vertical potential gradient. The density of this current, or strength per square centimeter cross section, may be computed from the potential gradient and the conductivity, or, with suitable apparatus, may be measured directly. The average value of this conduction current is of the order of 3×10^{-16} ampere per square centimeter of, apparently, the entire surface of the earth. It generally is less during the day than at night, and less in summer than winter; but always of such value that the sum total of the current for the entire earth is roughly 1500 amperes. How

this constant current, always, on the whole, in the same direction, is maintained is one of the greatest problems of atmospheric electricity.

Another of the great problems of atmospheric electricity is its possible relation to solar activity. Chree[10] and others have pointed out certain indications of a relationship between atmospheric electricity and sunspots, but no definite conclusions have yet been reached. The reason for this seems to be partly that meteorological factors such as are mentioned above unquestionably exert a great influence upon the electrical condition of the lower air. Moreover, it is not to be expected that a single station, or even the two or three for which moderately long records of atmospheric electricity are available, should show whatever solar relationships may exist as clearly as would a large number widely distributed. For a long time London (Kew) and Berlin (Potsdam) were the only stations for which continuous electrical records were available, and even now the number is very limited. Another difficulty has been that most investigators have used only the so-called quiet or undisturbed days, but these seem to give an imperfect record of the true conditions.

In spite of these difficulties there is a steady accumulation of evidence to show that atmospheric electricity belongs to the same general series as magnetism, auroras, and earth currents, and that all alike depend upon variations in the sun. This conclusion is supported by Bauer's study of the records of atmospheric potential gradients at the Observatorio del Ebro, Tortosa, Spain, from 1910 to 1920. He summarizes his results as follows:[11]

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[10] C. Chree: A discussion of atmospheric potential results at Kew from selected days during the seven years 1898 to 1904, Phil. Trans. Roy. Soc., Lon., Vol. 206 A, 1906, pp. 299-334.

[11] L. A. Bauer: Some Results of Recent Earth-Current Observations and

> On fine-weather, or electrically calm days the atmospheric potential gradient, or the deduced negative charge on the surface of the earth, increases with increased solar activity, the range in the variation between minimum and maximum solar activity being about 20 per cent. The electric activity of the atmosphere, on the other hand, shows but little, if any, systematic variation with the solar cycle. Accordingly, since the vertical conduction-current of atmospheric electricity is derived from the product of the potential gradient and the electrical conductivity, it is found that this vertical current also increases in strength with increased solar activity. It would thus appear that atmospheric electricity, like terrestrial magnetism, is controlled by cosmic factors.
>
> The diurnal range of the electrical potential gradient as deduced from the observations on the electrically calm days, made at the Observatorio del Ebro, Tortosa, Spain, 1910-1919, is found to increase with solar activity; the minimum occurred in 1911 and the maximum in 1917, whereas the sunspot minimum occurred in 1912 and the maximum in 1917. The range between minimum and maximum diurnal range is about 25 per cent.

Further evidence of the unity of all the electrical phenomena of the earth and hence of the solar relationships of atmospheric electricity is seen in Fig. 28. In this Bauer shows the variations in the four types of terrestrial electromagnetic phenomena by months. The second line gives the variations in atmospheric electrical potential on the quiet days from 1910 to 1920; next come the earth currents for all sorts of days at the same place and for the same period. The third line is based on the data of Ellis as to the number of auroras in different months in lati-

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Relations with Solar Activity, Terrestrial Magnetism, and Atmospheric Electricity; Terrestrial Magnetism and Atmospheric Electricity, Vol. 27, 1922, pp. 1-30.

L. A. Bauer: On Measures of the Earth's Magnetic and Electric Activity and Correlations with Polar Activity, Bull. Nat. Res. Coun., No. 17, 1922, pp. 59-65.

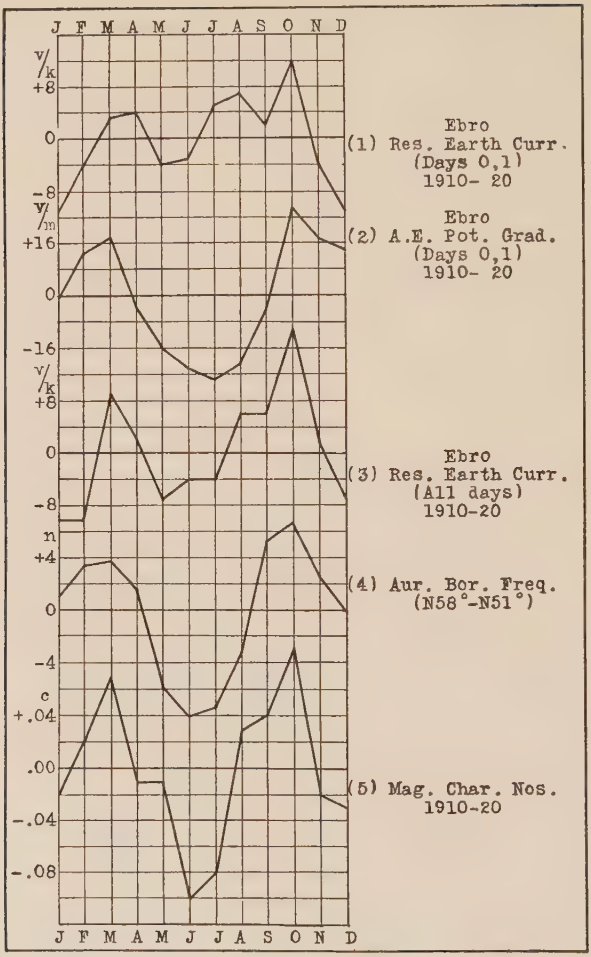

Fig. 28.

Annual Variations of Diurnal Range of Electric and Magnetic Phenomena.

(*After Bauer.*)

(*Courtesy of Department of Terrestrial Magnetism, Carnegie Institution of Washington.*)

tudes 51° to 58° N.; while the fourth shows the magnetic character numbers from 1910 to 1920, which Bauer says "may serve as measures of terrestrial magnetic disturbances in the course of the year." All the curves show maxima at or shortly after the solstices, the principal maximum in each case being in October, thus exhibiting a lag of perhaps a month with respect to the autumn equinox. The great similarity in the annual march of earth currents, atmospheric electricity, auroras, and magnetic disturbances seems to be a strong indication that all are due to the same cause, presumably the sun.

Still another line of evidence also points in the same direction. This is illustrated in Fig. 29, which shows how the potential gradient of atmospheric electricity varies from hour to hour over three widely separated oceans. The maximum gradient for each ocean occurs at a different hour according to local time, but these apparently different times are actually simultaneous, as appears in Fig. 29, where all the curves are drawn according to Greenwich time. Mauchly[12] discusses the matter as follows:

> From a comparison of these curves it appears that the daily maximum (likewise the minimum) of the potential gradient, over the oceans, occurs approximately simultaneously in all localities. The curve in the lower part of the figure represents the mean diurnal variation of the potential gradient as derived from the entire 45 series. The times of maximum and minimum as given by this curve (7 p.m. to 4 a.m., G. M. T.) probably represent only an approximate yearly average.
>
> However, it is significant to note that (a) in western Europe, where local time does not differ greatly from G. M. T., the occur-

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[12] S. J. Mauchly: Recent Results on the Diurnal Variation of Atmospheric Electricity from Observations aboard the *Carnegie*, Phys. Rev., Vol. 18, No. 2, pp. 161-162, and Jour. Wash. Acad. Sci., Vol. 11, No. 16, pp. 398-399. Abstract in Year Book No. 20, for the year 1921, Carnegie Institution of Washington, pp. 354-356.

rence of the chief daily minimum at approximately 4 a.m. is common to many stations; (b) the diurnal variation of the potential gradient as observed at practically all high-latitude stations and, in winter, at various stations in temperate latitudes,

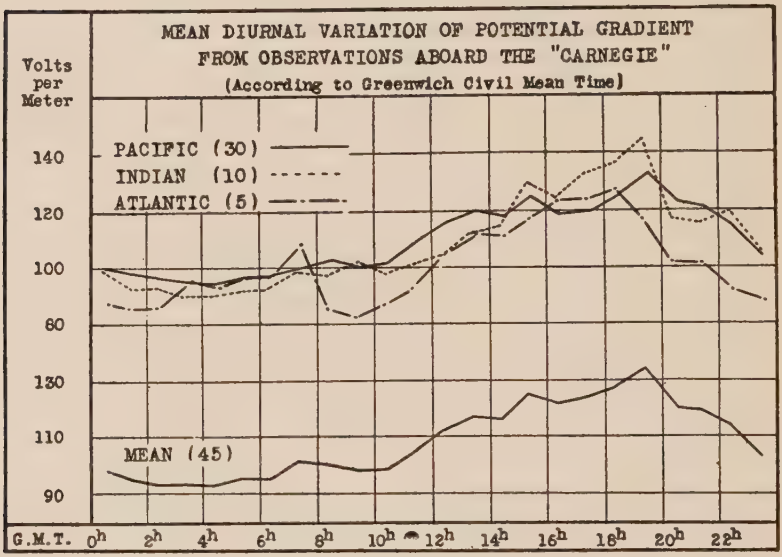

Fig. 29.

Mean Diurnal Variations of Potential Gradient of Atmospheric Electricity over the Oceans.

(*After Mauchly.*)

(*Courtesy of Department of Terrestrial Magnetism, Carnegie Institution of Washington.*)

is very similar to what has here been found for the ocean, when differences in local time are taken into account. It is also significant that Mache and v. Schweidler long ago called attention to the fact that the phase angle of only the 12-hour Fourier wave has roughly the same value for most stations, whereas the phase angle corresponding to the 24-hour wave varies greatly from station to station.

A fact of considerable interest is that the diurnal-variation curves for the potential gradient derived from the Carnegie observations are very similar to curves which represent the diurnal frequencies of the aurora borealis, as observed at several European stations, and also to curves representing the diurnal frequencies of certain classes of magnetic disturbances, when all are referred to the same time-basis. It may also be pointed out that owing to the non-coincidence of the earth's magnetic axis with its axis of rotation, the time of daily potential gradient maximum, as indicated by the ocean curves, corresponds approximately to the time when the earth's north magnetic pole, for example, is nearest to the sun, while the daily minimum occurs, in a general way, when this pole is farthest from the sun. The actual times of maximum and minimum, however, appear to depend upon the position of *both* magnetic poles and upon the fact that their longitude difference is not 180°. These correlations appear to support the assumptions of various investigators that the earth's electric charge and resultant field may be very intimately related to an electric radiation from the sun.

We have seen that there is evidence that atmospheric electricity shows a relation to the sun in its variations from year to year, from month to month, and from hour to hour. In the next chapter I shall present certain new evidence showing that the same is true for variations from day to day. We can carry the matter even farther, however, for the observations of eclipses made by Mauchly and Thomson[13] on behalf of the Department of Terrestrial Magnetism of the Carnegie Institution of Washington show that even from moment to moment the sun influences atmospheric electricity. At two successive eclipses it has been found not only that the shadowing of the sun is accompanied by magnetic changes, but also that

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[13] S. J. Mauchly and Andrew Thomson: Results of Atmospheric-Electric Observations at Sobral, Brazil, during the Total Solar Eclipse of May 29, 1919; Terrestrial Magnetism and Atmospheric Electricity, Vol. 25, 1920, pp. 41-48.

> (a) the potential gradient shows a well-formed minimum beginning with totality and extending until about 20 minutes after totality; the values observed during this period were about 20 per cent lower than the mean derived from two equal periods immediately preceding and following it. (b) During the period of potential gradient minimum the fluctuations of the gradient were very much smaller than during the similar periods preceding and following. (c) The positive and negative conductivities, and therefore the total conductivity also, each showed an increase of the order of 20 per cent, beginning just after totality and continuing for about 15 minutes. (d) The air-earth current density (product of simultaneous values of potential gradient and total conductivity) showed a greater constancy during the period in question than for any equal period throughout the forenoon of the day of the eclipse. The results for May 29, 1919, at Sobral, are in general agreement with those obtained at Lakin, during the eclipse of June 8, 1918, notwithstanding the great difference between the two stations as regards latitude, elevation, general topography, and distance from sea.[14]

In view of the foregoing facts we may tentatively accept the conclusion that atmospheric electricity, earth currents, auroras, and terrestrial magnetism are parts of a single group of phenomena and all are maintained and caused to vary by the activity of the sun. Other factors may indeed enter into the matter, as we know they do, but they merely modify and partially obscure the solar relationship. If we accept this conclusion we are confronted by the problem of how the sun exerts its electrical effect upon the earth.

The fact that the conduction current in the earth's atmosphere is usually positive and yet that the earth maintains its negative charge has been the subject of numerous hypotheses. Simpson,[15] Kolhörster,[15] and Swann[15] have all suggested that extremely hard or penetrating radiation of the gamma type must enter the lower atmosphere from somewhere above it. Since the vertical current is constant up to at least 1800 meters, the negative charge of the earth cannot be supplied from the air below that level, neither can it be supplied by a breaking up of electrical charges within the earth, for that would soon lead to a positive instead of a negative charge on the earth's surface. Since there is no reason to believe that the atmospheric conditions today are greatly different from what they were a hundred million years ago, it seems impossible that throughout this vast period the upper air itself can have supplied radiation of the type here postulated and still be able to supply more. Hence the only reasonable supposition seems to be, as Simpson and Kolhörster have both said, that the gamma rays must come from some cosmic source, apparently the sun.

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[14] L. A. Bauer: Some of the Chief Problems in Terrestrial Magnetism and Electricity, Proc. Nat. Acad. of Sci., Vol. 6, 1920, pp. 572-580.

Swann amplifies this hypothesis by stating that while the whole of the penetrating radiation is probably of the gamma ray type, that

> which reaches the earth's surface from the outer atmosphere is naturally the most penetrating part. Indeed, it is so penetrating that it passes through a thickness of air which would be equivalent, in absorptive action, to a column of mercury 76 cm. high, if absorption coefficients were simply proportional to density and were independent of material. The gamma ray radiation from the outer layers of the atmosphere will consequently be very "hard," and, in accordance with the known results of laboratory experiments, we must conclude that the negative corpuscles which it emits from the air molecules are emitted almost entirely in

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[15] G. C. Simpson: Mem. Ind. Meteor. Dept., Simla, Vol. 20, 1910; W. H. G. Kolhörster: Deutsch. Phys. Gesell., Vol. 16, 1914, p. 719; W. F. G. Swann: Phys. Rev., Vol. 9, 1917, p. 555.

the direction of the radiation, and further, that they can have a range in air at least equal to that of the swiftest beta rays from radium products, a range, for example, of 8 meters. The emission of corpuscles by these gamma rays will consequently result, at each point of the atmosphere, in a downward current of negative electricity, which we shall call the corpuscular current. This corpuscular current will charge the earth until the return conduction-current balances the corpuscular current at each point of the atmosphere.

In this connection the studies of Birkeland[16] are of interest. From certain experiments with magnetized spheres, which will be described later, he concludes

> that sunspots are really centers of emission for well-defined bundles of very hard cathode rays, producing auroras and magnetic perturbations on our earth. It would seem, from the analogies previously indicated, that sunspots may be the very emission centers from which disruptive electrical discharges emanate on the sun. I had previously found that these cathode rays, in the presence of magnetic forces, must have an enormous hardness, as indicated in the formula: H.S.$=3\times10^6$ C.G.S. units, according to which the intensity of the field multiplied by the radius of curvature of an element of a trajectory normal to the force is equal to three millions at every point. For the purpose of making a comparison which can be easily recalled, it may be observed that the same product, in round numbers, has for different types of rays the following values:
>
> For the cathode rays 300, for the beta rays of radium 3000, for the canal rays 30,000, for the alpha rays 300,000, and finally, for my helio-cathodic rays, 3,000,000.

Birkeland and Störmer think that the peculiar curtain-like appearance of the aurora indicates that it is due to types of electrical emanations which cannot travel far through the air, but are able to penetrate the tenuous upper layers of hydrogen and nitrogen and there produce phosphorescence. Such emanations soon become exhausted and simply stop, thus presumably creating the cloud fingers which we see occasionally in lower latitudes and which prevail very commonly in high latitudes.

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[16] Kr. Birkeland: The Origin of Worlds, Sci. Am. Supplement, Vol. 76, 1913.

Another not greatly dissimilar view is contained in the following quotation from Humphreys.[17]

> The fact that brilliant shifting auroras are accompanied by magnetic storms renders it practically certain that they, and presumably therefore all auroras, are due to electric discharges; and the further fact that they vary in frequency with the sun-spot period indicates that this current either comes from or is induced by the sun. For some time it was thought probable that auroras are caused by negative particles shot off from the sun, and entrapped by the magnetic field of the earth. On the other hand, Vegard has given strong arguments in favor of the alpha particle which is positively charged, and Störmer has found at least one case that required the positive charge to account for the observed magnetic disturbance.
>
> The evidence, then, while not conclusive, indicates that auroras are due to streams of alpha particles in the upper atmosphere shot off by radioactive substances in the sun.

Chapman[18] is another investigator who has developed an hypothesis of a stream of charged particles emanating from the sun and striking the earth's upper atmosphere. Lindemann[19] suggests a modification of this to the effect that clouds of ionized gas are ejected from the sun and are driven away by the pressure of light. Such a cloud would be completely ionized, and therefore invisible; it would be kept together because it contains both positive and negative ions; but it would expand sufficiently so that the passage of the earth through it would take time enough to account for the duration of magnetic storms and other electromagnetic phenomena. In the earth's upper air the ions are supposed to recombine and give rise to magnetic storms.

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[17] W. J. Humphreys: Physics of the Air, 1920.

[18] Chapman: Proc. Roy. Soc., Vol. 95 A, 1918, pp. 61-83; also Monthly Notices of R. A. S., Nov., 1918, pp. 70-83; and Observatory, Lon., Vol. 42, No. 539, May, 1919, pp. 196-206.

[19] F. A. Lindemann: Phil. Mag., Dec., 1919, pp. 669-684.

Bauer has not advanced a definite hypothesis as to the nature of the supposed emanations from the sun, but his study of electrical currents both in the earth and the air causes him to conclude that

> we apparently have, on the average, negative electricity streaming into the earth in the polar regions, or regions of pronounced polar lights, and streaming out into the air in lower latitudes. Or, we may say also that we apparently have, on the average, negative electricity streaming into the earth in polar regions, and positive electricity streaming into the earth in lower latitudes. . . . To account for the strength of the vertical currents apparently disclosed by magnetic observations, it [seems] necessary to assume the existence of a corpuscular current of such extraordinarily high penetrability as to get through the atmosphere and penetrate the earth's surface. . . . The so-called ''penetrating radiation,'' the cause of which has not yet been satisfactorily explained, [seems] further to indicate that something of a highly penetrating character does actually get through the atmosphere and down to the surface of the earth. To add to the interest of the matter, the normal potential-gradient and corresponding vertical conduction-current of atmospheric electricity, and their variations, . . . are found to be related to solar activity and to the relative positions of the sun and earth and possibly of other planetary bodies, in much the same manner as the earth's magnetic state and polar lights have long been known to be.[20]

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[20] L. A. Bauer: Measures of the Electric and Magnetic Activity of the Sun and the Earth, and Interrelations; Terrestrial Magnetism and Electricity, March and June, 1921, pp. 33-34.

The conclusion that the sun sends out electrical emissions is in accordance with the well-established law that all hot bodies emit electrons or other forms of electrical energy. As Bosler[21] puts it,

> At temperatures of about 1500°C., Richardson and Harker obtained currents of 1 ampere per square centimeter of heated surface. The law connecting the current with the temperature is exponential. The emission from the sun must, therefore, be considerable. Further, the spectrum of the chromosphere includes a great number of lines which can be reproduced in the laboratory only by electrical processes. . . . We are thus almost inevitably led to conclude that the sun is . . . the seat of huge convection currents of charged matter.

The work of Hale[22] and his collaborators at the Mount Wilson Observatory puts this conclusion on an observational basis. They have measured the sun's magnetic field by means of the Zeeman effect. They find that the general field at the poles has a strength of about 50 gausses, or 80 times that of the earth. In sunspots the strength increases and may become as high as 4500 gausses. Since a hot body cannot be permanently magnetized, it follows that the sun must be the seat of strong electrical currents which constantly renew the magnetization. Variations in the strength of the currents must be accompanied by variations in the strength of the general magnetic field. They must also be accompanied by variations in the emission of electrons.

The facts contained in the preceding pages seem to warrant the following conclusions:

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[21] Jean Bosler: Modern Theories of the Sun, Ann. Rep. Smiths. Inst., 1914, p. 150.

[22] Geo. E. Hale: Contr. fr. Mt. Wilson Observ., Nos. 30, 1908, and 71, 1913; reprinted from Astrophysical Journal, Vol. 28, 1908, pp. 315-343, and Vol. 38, 1913. See also The Earth and the Sun as Magnets, Ann. Rep. Smiths. Inst., 1913, pp. 145-158.

(1) The electrical and magnetic phenomena of the earth fall into at least four great classes, namely, magnetism, auroras, earth currents, and atmospheric electricity. The first two are the best known; it is almost universally agreed that they vary in harmony with solar activity as shown in sunspots, prominences, and other disturbances.

(2) Recent investigations show that earth currents bear a close relationship to terrestrial magnetism. While the observational data are still scanty, they seem to indicate that the solar relationships of earth currents resemble those of magnetism and auroras.

(3) With atmospheric electricity the case is not quite so clear because this is strongly influenced by meteorological conditions such as convection, rain and snow, fogs, clouds, and winds. These local and temporary effects, however, can largely be eliminated by employing data for long periods and many regions. When this is done, three great facts stand out clearly. First, it is impossible to explain the maintenance of the electrical charge of the earth and its atmosphere, and especially the increase of that charge at high levels, without assuming some powerful and persistent outside source of energy such as emanations from the sun. Second, the variations in atmospheric electricity from hour to hour, month to month, and year to year show a strong agreement with those of magnetism, auroras, and earth currents. Third, the relation of the variations in atmospheric electricity to the sunspot cycle, to eclipses, and to the position of the earth's magnetic poles in respect to the sun suggests that solar variations are the cause of the terrestrial variations.

(4) That the sun is highly active electrically and that it sends out electrical emissions seems to be established almost beyond question. It has also been demonstrated

that the electrical activity varies in fairly close harmony with sunspots and with the solar constant.

On the basis of all the facts yet known it seems highly probable that terrestrial magnetism, auroras, earth currents, and atmospheric electricity are a series of closely related phenomena, all of which owe much of their energy to electrical emanations from the sun, and all of which vary more or less closely in harmony with disturbances of the sun's atmosphere.

CHAPTER VII

THE ELECTRICALLY EFFECTIVE AREAS OF THE SUN

IT has frequently been stated that different parts of the sun's disk are diverse in the nature and strength of their influence upon the earth. The determination of the truth of this statement is a necessary preliminary to accurate measurement of the amount of solar energy available at any special time for the production of terrestrial auroras, magnetic variations, earth currents, and atmospheric electricity. Moreover, the distribution of effective areas upon the sun's surface may furnish evidence as to the nature of the electrical connection between the earth and the sun, and as to the degree to which the earth's weather may depend upon the sun's electrical condition as well as upon its emission of radiation in the form of light.

One way in which to gain light on the problem of whether the various parts of the solar disk differ in their electrical activity is to compare the electrical potential of the earth's atmosphere with the spots on specific parts of the sun's disk. Unfortunately, long records of atmospheric electricity are very few in number. Previous to 1910, Kew and Potsdam are the only stations for which full daily records are available for many years in printed form. Nevertheless, it seems necessary to use the period previous to 1910, for only thus can we make comparisons with barometric gradients over the Atlantic Ocean at times of abundant sunspots, as is done in a later chapter. The Great War delayed the publication of many records pertaining to the sunspot maximum of 1917. Accordingly we shall use the records of daily atmospheric electrical potential gradients at Kew for the six years 1904 to 1909. In view of the electrical instability of the vicinity of London these records need to be checked against the later and more stable records at such places as Ebro in Spain as soon as possible. Nevertheless, our results are surprisingly clear-cut. The years 1904-1909 were a time of fairly abundant sunspots. During years of few spots electrical disturbances doubtless occur upon the sun, but as yet we have no record of them, and hence should fall into error if we assumed that no sunspots mean no electrical disturbances. Hale,[1] in fact, has recently measured electrical disturbances on the sun which cannot be detected either by the eye or by the camera.

The first step in the present investigation is to divide the sun's disk into twelve sections, as shown in Fig. 30, each section being 30° wide and extending from the equator to one of the poles. The outer sections, when seen from the earth, appear very narrow, for their curved surfaces lie almost in the line of vision. Hence many small spots are entirely invisible, although they would appear if in a central section. Even when full allowance is made for foreshortening, as is done in all our data, the apparent spottedness of the sections at various distances from the central meridian of the solar disk is as follows: 0°—30°=173, 30°—60°=157, and 60°—90°=100.

Having made the division into sections, the next step is to determine the correlation coefficients between the daily areas of the sunspots in each section and the electrical gradients at Kew on the same day. The areas of the sunspots were determined by the tedious process of adding the areas of the umbræ or inner dark portions of all the individual spots. It might have been better to use the entire areas, but the umbræ give smaller and more convenient numbers and the ratio between the whole areas and those of the umbræ is so nearly uniform that the final results are essentially the same in either case. The daily figures for electrical gradients were obtained by averaging the observations for 24 hours as given in the Greenwich tables.

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[1] G. E. Hale: Invisible Sunspots, Proc. Nat. Acad. Sci., Vol. 8, 1922, pp. 168-170.

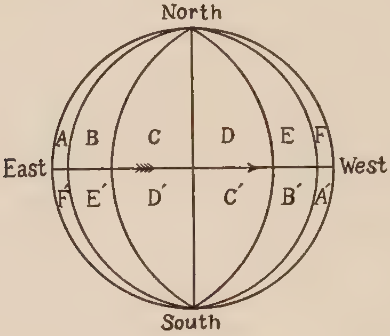

Fig. 30.

Division of the Sun's Surface into Sections for Correlation with Atmospheric Electricity.

The correlation coefficients derived in this way are given in Table 18. Before discussing them, let us inquire what we should expect. Even if atmospheric electricity is ultimately dependent upon electrical emanations from the sun, the electrical potential gradient of the lower atmosphere on any given day may depart widely from what would be expected on the basis of the sun alone. In the first place, the terrestrial effect may lag after its solar

TABLE 18

CORRELATION COEFFICIENTS BETWEEN ELECTRICAL POTENTIAL AT LONDON (KEW) AND SUNSPOTS ON VARIOUS PARTS OF THE SUN'S SURFACE

	No. of days	$P\times A$	$P\times B$	$P\times C$	$P\times D$	$P\times E$	$P\times F$	$P\times F'$	$P\times E'$	$P\times D'$	$P\times C'$	$P\times B'$	$P\times A'$
Jan.	165	0.085	0.118	0.086	0.026	0.114	*0.149*	0.039	0.065	*0.184*	—0.076	—0.034	—0.132
Feb.	169	—0.067	—0.135	0.113	0.082	0.133	0.087	0.129	—0.000	—0.058	0.052	—0.120	—0.079
Mar.	179	—0.081	—0.014	0.003	0.092	0.155	0.014	0.103	**0.246**	0.129	*0.179*	0.114	—0.093
Apr.	178	0.017	0.030	**0.335**	0.041	*0.158*	*0.170*	—0.050	0.013	0.028	0.004	0.011	0.063
May	178	*—0.156*	—0.103	0.122	—0.074	0.009	—0.051	0.050	0.073	0.035	0.044	0.008	—0.036
June	180	—0.013	0.088	0.074	0.093	**0.208**	**0.199**	0.046	—0.005	0.017	—0.001	0.102	0.023
July	170	0.026	0.042	—0.019	0.087	0.075	0.075	**0.193**	*0.173*	—0.003	0.041	—0.012	—0.037
Aug.	146	—0.051	0.116	—0.092	—0.027	—0.056	0.040	—0.041	0.045	0.064	0.011	0.022	0.129
Sept.	170	—0.135	—0.043	—0.003	—0.037	—0.122	—0.104	**—0.204**	*—0.178*	—0.133	—0.107	—0.132	—0.106
Oct.	167	0.148	**0.246**	**0.240**	*0.185*	0.131	*0.168*	—0.079	—0.104	—0.132	—0.086	—0.122	—0.116
Nov.	168	—0.031	0.053	—0.075	—0.025	—0.046	0.019	—0.006	0.033	0.065	—0.084	—0.026	—0.018
Dec.	173	—0.013	—0.071	*—0.156*	—0.029	0.031	—0.021	0.029	0.119	—0.061	—0.020	0.097	0.042
Year	2043	0.004	*0.049*	*0.051*	0.043	*0.051*	*0.050*	0.023	0.038	0.008	0.010	—0.025	—0.038

P=Electrical potential at Kew
A=Spots in sun's N.E. quadrant 60-90° from central meridian
B=Spots in sun's N.E. quadrant 30-60° from central meridian
C=Spots in sun's N.E. quadrant 0-30° from central meridian
D=Spots in sun's N.W. quadrant 0-30° from central meridian
E=Spots in sun's N.W. quadrant 30-60° from central meridian
F=Spots in sun's N.W. quadrant 60-90° from central meridian
F′=Spots in sun's S.E. quadrant 60-90° from central meridian
E′=Spots in sun's S.E. quadrant 30-60° from central meridian
D′=Spots in sun's S.E. quadrant 0-30° from central meridian
C′=Spots in sun's S.W. quadrant 0-30° from central meridian
B′=Spots in sun's S.W. quadrant 30-60° from central meridian
A′=Spots in sun's S.W. quadrant 60-90° from central meridian

Probable error for monthly figures, ±0.048 to ±0.053
Probable error for annual figures, ±0.0156 to ±0.0157
Coefficients more than 3 times the probable error are indicated by the use of italic figures, thus (*—0.156*); more than 4 times by the use of large black type, thus (**0.246**).

cause. Second, all sorts of terrestrial conditions may and do have a great effect upon the electrical condition of the atmosphere. An important place among the terrestrial conditions is held by convection, whereby the air with its accompanying electrical charge is bodily carried upward or downward in vast quantities. The greater the convection, the more closely the electrical potential gradient will be correlated with it and the less closely with the sun. Hence we should expect the solar relationship, if such there is, to be more obvious in winter than in summer.

Again, in the preceding chapter we saw that the potential gradient is higher in clear areas of high barometric pressure than in cloudy, rainy areas of low pressure. In Table 19, section 5, this relationship is seen to be so close that when the daily potential gradient and the pressure at Kew are compared for the years 1904 to 1909 they show a positive correlation coefficient nearly nineteen times the probable error. This relationship is far stronger in summer than in winter. Rainfall likewise is a major factor in determining the potential gradient of the atmosphere, as we saw in discussing Simpson's results. How closely the two are correlated appears in Table 19, section 6, where the coefficient for the six years 1904 to 1909 is —0.270, or almost exactly 20 times the probable error. Here again the strength of the correlation varies greatly, being high in the half-year from January to June, with a maximum in March, and low in a general way throughout the rest of the year. Other factors also influence the electrical condition of the lower atmosphere. Hence, even if solar emissions were the sole source of atmospheric electricity, which presumably is not the case, and even if the electrical charge of the upper air depended wholly on solar emissions, which probably is not true, we should expect the lower air to show only a low correlation with daily changes in the electrical condition of the sun. Because of the disturbing effect of convection, we should also expect the correlation to be clearer in winter than in summer.

TABLE 19

CORRELATION COEFFICIENTS: DAILY SUNSPOTS AND METEOROLOGICAL DATA, 1904-1909

A=Barometric gradients over the northern section of the North Atlantic Ocean
B=Barometric pressure at London (Kew)
O=Ozone at London (Kew)
P=Atmospheric electrical potential gradient at London (Kew)
R=Rainfall at London (Kew)
S=Sunspots, that is area of umbræ (B+C+D+E+F)+(F′+E′)—(A′+B′), omitting A, C′ and D′. For location of sections A, B, etc., see Fig. 30
r=Correlation coefficient
e=Probable error
r/e=Correlation ratio

	1.			2.		
	SUNSPOTS × POTENTIAL GRADIENT (KEW)			SUNSPOTS × BAROMETRIC PRESSURE (KEW)		
	S × P			S × B		
	r	*e*	*r/e*	*r*	*e*	*r/e*
Jan.	+0.244	±0.049	5.0	+0.068	±0.050	1.4
Feb.	+0.354	±0.046	7.7	+0.067	±0.052	1.3
Mar.	+0.063	±0.050	1.3	+0.034	±0.050	0.7
Apr.	+0.162	±0.049	3.3	—0.100	±0.050	2.0
May	+0.002	±0.051	0.0	+0.088	±0.050	1.8
June	—0.047	±0.051	0.9	+0.019	±0.050	0.4
July	+0.257	±0.047	5.5	+0.109	±0.049	2.2
Aug.	—0.151	±0.049	3.1	—0.192	±0.048	4.0
Sept.	—0.090	+0.052	1.7	—0.183	±0.049	3.7
Oct.	+0.570	±0.035	16.3	+0.143	±0.049	2.9
Nov.	+0.038	±0.052	0.7	+0.101	±0.050	2.0
Dec.	+0.093	±0.052	1.8	—0.219	±0.047	4.7
Year	+0.141	±0.0145	9.7	+0.003	±0.014	0.2

	3. Sunspots × Barometric Gradients over North Atlantic Ocean S × A			4. Sunspots × Rainfall (Kew) S × R		
	r	*e*	*r/e*	*r*	*e*	*r/e*
Jan.	—0.019	±0.053	0.4	—0.071	±0.050	1.4
Feb.	—0.316	±0.048	6.6	—0.104	±0.051	2.0
Mar.	—0.051	±0.050	1.0	+0.069	±0.050	1.4
Apr.	+0.002	±0.050	0.0	+0.053	±0.050	1.1
May	—0.141	±0.048	2.9	—0.023	±0.050	0.5
June	—0.156	±0.048	3.3	+0.067	±0.050	1.3
July	+0.011	±0.050	0.2	—0.132	±0.049	2.7
Aug.	+0.244	±0.047	5.2	+0.062	±0.050	1.2
Sept.	+0.053	±0.050	1.1	—0.035	±0.050	0.7
Oct.	—0.206	±0.047	4.4	—0.146	±0.048	3.0
Nov.	+0.108	±0.049	2.2	+0.038	±0.050	0.8
Dec.	+0.075	±0.050	2.5	+0.237	±0.047	5.0
Year	—0.034	±0.0145	2.3	—0.008	±0.0145	0.6

	5. Potential Gradient (Kew) × Barometric Pressure (Kew) P × B			6. Potential Gradient (Kew) × Rainfall (Kew) P × R		
	r	*e*	*r/e*	*r*	*e*	*r/e*
Jan.	+0.138	±0.053	2.6	—0.388	±0.046	8.4
Feb.	+0.276	±0.049	5.6	—0.420	±0.042	10.0
Mar.	+0.376	±0.044	8.5	—0.493	±0.039	12.7
Apr.	+0.214	±0.048	4.5	—0.477	±0.039	12.2
May	+0.284	±0.047	6.0	—0.274	±0.046	6.0
June	+0.407	±0.042	9.7	—0.287	±0.046	6.2
July	+0.329	±0.046	7.2	—0.203	±0.050	4.1
Aug.	+0.322	±0.045	7.2	—0.301	±0.046	6.6
Sept.	+0.297	±0.046	6.5	—0.178	±0.050	3.8
Oct.	+0.302	±0.046	6.6	—0.274	±0.048	5.7
Nov.	+0.074	±0.054	1.4	—0.105	±0.051	2.1
Dec.	+0.165	±0.050	3.3	—0.153	±0.050	3.1
Year	+0.256	±0.0138	18.7	—0.270	±0.0135	20.0

	7.			8.		
	Barometric Pressure (Kew) × Rainfall (Kew)			Potential Gradient (Kew) × Barometric Gradients over North Atlantic Ocean		
	B × R			P × A		
	r	*e*	*r/e*	*r*	*e*	*r/e*
Jan.	—0.511	±0.037	13.8	—0.309	±0.051	6.1
Feb.	—0.472	±0.040	11.8	—0.232	±0.052	4.5
Mar.	—0.453	±0.039	11.5	—0.144	±0.051	2.8
Apr.	—0.429	±0.041	10.5	—0.112	±0.050	2.2
May	—0.228	±0.047	4.8	—0.229	±0.047	4.9
June	—0.312	±0.046	6.8	—0.032	±0.050	0.6
July	—0.284	±0.046	6.2	—0.197	±0.050	3.9
Aug.	—0.366	±0.043	8.5	—0.354	±0.044	8.1
Sept.	—0.294	±0.046	6.4	—0.250	±0.048	5.2
Oct.	—0.244	±0.047	5.2	—0.262	±0.048	5.5
Nov.	—0.465	±0.040	11.6	—0.164	±0.050	3.3
Dec.	—0.468	±0.040	11.7	—0.180	±0.050	3.6
Year	—0.365	±0.0126	29.0	—0.199	±0.0140	14.2

	9.			10.		
	Barometric Pressure (Kew) × Barometric Gradients over North Atlantic Ocean			Potential Gradient (Kew) × Ozone (Kew)		
	B × A			P × O		
	r	*e*	*r/e*	*r*	*e*	*r/e*
Jan.	—0.373	±0.046	8.1	—0.277	±0.049	5.7
Feb.	—0.216	±0.051	4.2	—0.256	±0.049	5.2
Mar.	—0.151	±0.050	3.0	—0.318	±0.046	6.9
Apr.	—0.163	±0.049	3.3	—0.372	±0.044	8.4
May	—0.111	±0.049	2.3	—0.313	±0.044	7.1
June	—0.139	±0.049	2.8	—0.323	±0.044	7.3
July	—0.182	±0.049	3.7	—0.120	±0.050	2.4
Aug.	—0.253	±0.048	5.3	—0.363	±0.044	8.2
Sept.	—0.076	±0.050	1.5	—0.169	±0.050	3.4
Oct.	—0.260	±0.048	5.4	—0.342	±0.046	7.4
Nov.	—0.008	±0.050	0.2	—0.340	±0.046	7.4
Dec.	—0.255	±0.048	5.3	—0.378	±0.045	8.4
Year	—0.185	±0.0140	13.2	—0.251	±0.0138	18.2

Turning now to the sun, its conditions would no more lead us to expect a high correlation between sunspots and the potential gradient of the atmosphere than would the terrestrial conditions. In the first place, sunspots are only an imperfect measure of solar activity; not only are some of the sun's electrical activities unaccompanied by visible effects, but the electrical activity of a sunspot by no means varies in direct proportion to the size of the spot. Moreover, we are here dividing the sun's visible disk into twelve small units, and are making no allowance for any lag between cause and effect. Thus, whether we look at the matter from the terrestrial or the solar standpoint, we should expect only small correlation coefficients, even though the ultimate relation between solar and terrestrial electricity may be close. And we should expect the relationship to be greater in winter and when convection is slight, as at times of high barometric pressure, than in summer and at times of low barometric pressure, when great masses of air are welling upward in the central parts of storms. To put it in another way, all that we can expect from the present method is some indication of the kind of relationship, but little or no information as to its real strength. Small correlation coefficients may be of much significance, provided they are systematic.

Bearing in mind, then, the limitations and purposes of the present method, let us examine Table 18 and also Fig. 31, where graphs of the average coefficients for four seasons and for the year are given. The solid lines represent the correlation coefficients between the potential gradient at Kew and the sunspots in the various sections of the sun's northern hemisphere from A to F in Fig. 30. The dotted lines represent similar coefficients for the sun's southern hemisphere, A′ to F′ in Fig. 30. The horizontal dash lines indicate the approximate position of the probable error, although of course this varies according to the size of the coefficients. In order to bring out the inverse similarity between the terrestrial relationships of the sun's northern and southern hemispheres, a lower series of diagrams has been added in which the coefficients from A′ to F′ run from left to right like A to F, instead of in the opposite direction, which is their actual position as shown in Fig. 30.

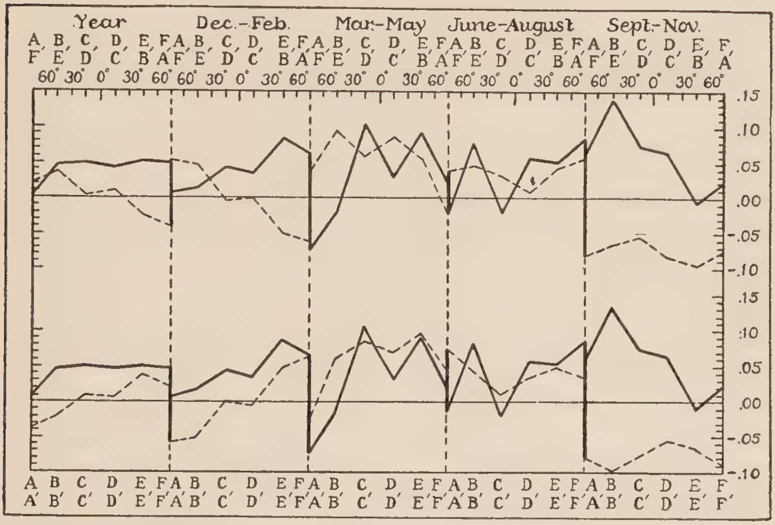

Fig. 31.

Correlation Coefficients between Daily Electrical Potential Gradients at Kew and Sunspots in Twelve Solar Sections, 1904-1909.

Solid lines=northern solar hemisphere.
Dotted lines=southern solar hemisphere.
Degrees indicate distance from sun's central meridian. Letters refer to sections of solar disk as illustrated in Fig. 30.

In the upper set of diagrams in Fig. 31 there is a general tendency for the solid lines representing the northern hemisphere to slope upward from left to right and for the dotted lines representing the southern hemisphere to slope in the opposite direction. This tendency disappears in the diagram for August to October, it is weakly developed from November to January, and strong for the other two seasons, as well as for the year as a whole. Taking the year as a whole, when spots appear on the sun's eastern margin in the northern hemisphere at A in Fig. 30, they show no appreciable correlation with the potential gradient at Kew, for the correlation coefficient is practically zero (+0.004). But as the spots cross the sun's disk they become more and more highly correlated with the gradient until a maximum of +0.051 (±0.0156) in C and E and of +0.050 (±0.0156) in F is reached. As the spots are about to disappear on the western margin of the solar disk their positive correlation with the potential gradient is probably higher than in the parts of the solar disk near the central meridian, for the coefficients in E and F are as high as in C and D, although many spots are invisible because sections E and especially F are turned away from the earth, as explained above. In the southern solar hemisphere, the conditions are the reverse of those in the northern. When the spots first appear at F′ they show a small positive correlation of +0.023 (±0.0157), and this rises to +0.038 in E′, that is, in the section 30°-60° east of the sun's central meridian. Then the correlation sinks to zero, and finally becomes negative, —0.038, so that spots on the southwestern margin of the sun's disk are correlated with low potential gradients.

In the lower part of Fig. 31, where the lines for the southern hemisphere have been reversed so that what is really the right side falls on the left, the inverse similarity of the two solar hemispheres is very clear. From February to April and from May to July the diagonally opposite parts of the sun's disk have almost identically the same relation to atmospheric electricity at Kew, as appears in the almost complete parallelism of the solid and dotted lines; from November to January the same is true to a less degree. Only from August to October does the parallelism break down.

So far as the statistical significance of Fig. 31 is concerned, the correlation coefficients are all small, the highest for any period of three months being 0.150. This, however, is over five times the probable error, and hence would presumably be significant even if we were dealing with the whole of the sun's disk instead of with only a twelfth.[2] Many other coefficients are from two to four times the probable error, and are probably significant in view of the small parts of the sun's disk with which they deal and their systematic arrangement. It is noticeable that the size of the coefficients varies greatly from season to season. This variation agrees closely with the strength of the potential gradients at Kew, as appears in Fig. 32. There the upper curve shows the average coefficients for the twelve sections of the sun month by month and the average potential gradient at Kew. Both curves have been smoothed to eliminate minor irregularities. Both show a pronounced maximum in March and a minimum in September or October. If the data of Table 18 are plotted by months instead of by periods of three months, as is done in Fig. 31, it is noticeable that March is the month when the reversal between the curves for the northern and southern hemispheres of the sun is most complete, while October is the month in which they are most alike, but also most widely separated. On the whole, the sun's

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[2] In Table 19, section 7, it will be noted that even for two phenomena so closely and obviously associated as rainfall and barometric pressure, the correlation coefficient for daily observations at Kew from 1904 to 1909 is only —0.365.

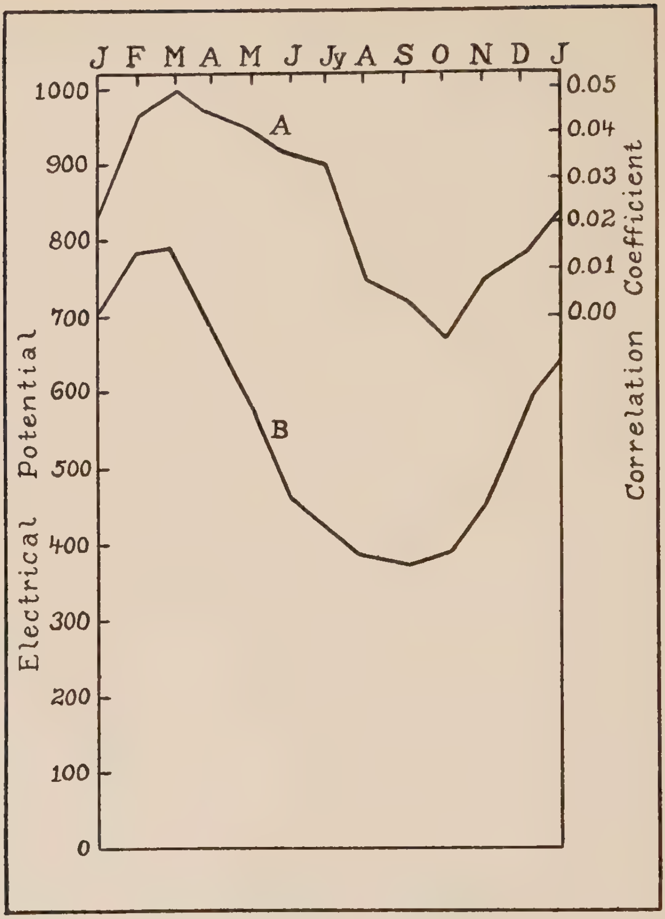

Fig. 32.

Seasonal Variations in Correlation Coefficients between Sunspots and Electrical Gradients at Kew, compared with Seasonal Variations in Electrical Gradients at Kew.

A. Average monthly values of correlation coefficients for twelve solar sections (see Fig. 30) compared with electrical potential gradients, 1904-1909.
B. Electrical potential gradients at Kew. Both curves smoothed by $\frac{a+b+c}{3}$

activity and the electrical potential gradient show a close relation when the gradient is high and little relation when the gradient is low.

Let us test the matter by still another set of correlation coefficients in which we combine all parts of the sun's disk. Table 18 shows that for the year as a whole sunspots in sections B to F, F′ and E′ have a positive correlation with the potential gradient at Kew; those in A′ and B′ have a negative correlation; while those in A, C′, and D′ have correlations too small to be significant. On the assumption that this represents approximately the true degree and kind of relationship, correlation coefficients for each month and for the year have been computed between the daily potential gradients at Kew and the effective areas of solar umbræ.[3] The results appear in part 1 of Table 19.

[3] It is not to be expected that we have yet found the best method of computing the effective area of sunspots. It is quite possible that much larger coefficients would result from some combination different from the one used above. Several have been tested for the months from January to April. They give the following results when compared with the daily electrical potential gradient at Kew from 1904 to 1909.

	Correlation coefficient r	*Probable error* e	*Ratio* r/e
1. All spots	+0.135	±0.025	5.4
2. All spots weighted as follows: F and F′=6; C and C′=3 E and E′=5; B and B′=2 D and D′=4; A and A′=1	+0.160	±0.025	6.4
3. All spots except in sections B, B′, A and A′	+0.166	±0.025	6.6
4. Spots selected per Table 18, as described in text, viz.: B+C+D+E+F+E′+F′—(A′+B′)	+0.183	±0.025	7.4

All of these coefficients are so large in proportion to the probable error that there is only one chance in thousands that even the smallest of them is due to accident. See page 28.

Although the coefficients of individual months vary greatly, the final coefficient for the whole year, 0.141, is 9.7 times the probable error. In other words, the odds are billions, or even millions of billions, to one against the possibility that the apparent relation between atmospheric electricity and the spots on various parts of the sun's surface is the result of accident. When the monthly coefficients are smoothed in order to eliminate minor irregularities and permit the general trend to become apparent, the result is the upper curve of Fig. 32. For the six months from October to March the curve is well above the level, which here represents approximately four times the probable error.

In view of the many nonsolar factors which influence the electrical condition of the earth's lower atmosphere the various facts stated above and especially the fact that the final correlation coefficient based on the 2043 available days during six years is nearly ten times the probable error makes it fairly certain that variations in the electrical activity of the sun are an important determinant of the electrical conditions of the earth's atmosphere, even in its lower and more perturbed portions where terrestrial factors are also highly important. It seems almost equally certain that all parts of the sun's disk do not have the same electrical effect. The greatest effect is apparently produced by the spots or electrical disturbances near the margins of the solar disk. Taking the year as a whole, a spot on the eastern margin in the sun's northern hemisphere seems either to have no effect on the atmosphere at London or else to reduce the normal negative potential gradient. When the same spot reaches the western margin of the solar disk it appears to produce a maximum effect in raising the potential gradient. A spot in the southern solar hemisphere likewise seems to produce different results when on the sun's eastern and western margins, but there is a reversal between the northern and southern hemispheres. In other words, the general rule appears to be that a spot in the northern part of the sun's disk has an opposite effect from a spot in the south, provided both are on the same side of the central meridian; while a spot in the east has an opposite effect from a spot in the west, provided both are on the same side of the equator. Still another way of putting it is that judging from the years 1904 to 1909, spots on diagonally opposite margins of the sun would seem to have the same kind of effect on atmospheric electricity, while spots in the northeast and southwest quadrants have an opposite effect from that of spots in the northwest and southeast quadrants. This seems unreasonable, but we shall shortly see that it at least corresponds to a peculiar feature of sunspots.

In the preceding investigation we have been hampered by the fact that in the outer sections of the sun's disk many small spots are invisible, so that even when full allowance is made for foreshortening, the apparent spottedness within 30° of the sun's margins is little more than half as great as within 30° of the central meridian. We can partly obviate this by taking the spots near the central meridian and finding their correlation with the atmospheric electrical potential for a series of days before and after the day when the spots are observed. Thus we can, as it were, carry a given group of spots from the time it is behind the sun through the time when it appears on the eastern margin and onward until it again disappears on the western margin. The only trouble is that the size of any given sunspot changes from day to day. During the six or seven days between the appearance of spots on the eastern margin and their arrival at the center of the disk, some spots may completely disappear; new ones may burst out; while even a large and relatively permanent spot may notably change its size. Similar changes may take place during the six or seven days during which a spot is carried across the rest of the solar disk before disappearing on the western margin. The uncertainty thus introduced, however, is different from the uncertainty due to the invisibilty of spots near the sun's margin. Hence we may profitably use this method and see how our results compare with those of the previous method. We will use the spots observed each day within 30° of the central meridian in the northeast and southeast quadrants of the solar disk.

In view of the change in the area of the sunspots as they cross the sun's disk, and in view of our previous conclusion as to the difference between the effect of spots on different parts of the disk, we should expect that our present method of calculating correlation coefficients would give two or even three periods of significant correlation. One would be at or near the zero day, that is, the day when the spots are measured as being in the section within 30° east of the central meridian. That day would show a relatively high correlation because that is the day when the exact area of the spots is known. The other high correlations would come on the days when the spots are at the solar longitudes where they have the greatest effect, either positive or negative.

This is just what we find, as appears in Table 20 and Fig. 33. Several features stand out clearly:

(1) The correlation of atmospheric potential gradients with spots in the sun's northern hemisphere is positive, no matter what part of the sun's disk the spots occupy.

This may have something to do with the fact that we are dealing with a high northern latitude on the earth, London being in latitude 51½° N.

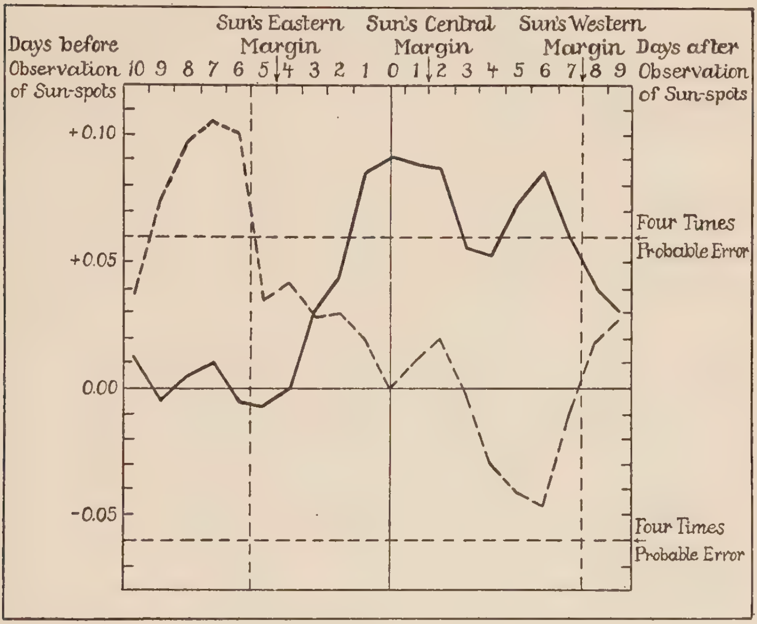

Fig. 33.

Relation of Northern and Southern Solar Areas to Atmospheric Electricity at Kew, 1904-1909.

Solid line=correlation coefficients between sunspot areas within 30° of sun's central meridian in northeast solar quadrant and daily electrical potential gradients at Kew on day of observation of spots and on 10 preceding and 9 following days.
Dotted line=same for spots within 30° of meridian in southeast quadrant.

(2) The correlation of the potential gradients with spots in the sun's southern hemisphere is positive when the spots are east of the central meridian, and negative when the spots are west of the meridian.

TABLE 20

CORRELATION COEFFICIENTS BETWEEN DAILY SUNSPOTS WITHIN 30° OF THE CENTRAL MERIDIAN AND ELECTRICAL POTENTIAL GRADIENTS AT KEW, 1904-1909

		Southeast solar quadrant		*Northeast solar quadrant*	
	Days before or after electrical gradients	*Correlation coefficient*	*Ratio of coefficient to probable error*	*Correlation coefficient*	*Ratio of coefficient to probable error*
Days before	—10	+0.039	2.6	+0.012	0.8
	—9	+0.073	*4.9*	—0.004	0.3
	—8	+0.096	*6.4*	+0.006	0.4
	—7	+0.105	*7.0*	+0.009	0.6
	—6	+0.099	*6.6*	—0.006	0.4
	—5	+0.039	2.6	—0.007	0.5
	—4	+0.048	3.2	0.000	0.0
	—3	+0.028	1.9	+0.032	2.1
	—2	+0.029	1.9	+0.047	3.1
	—1	+0.019	1.3	+0.087	*5.8*
	0	—0.002	0.1	+0.092	*6.1*
Days after	1	+0.011	0.7	+0.089	*5.9*
	2	+0.020	1.3	+0.087	*5.8*
	3	—0.002	0.1	+0.057	3.8
	4	—0.030	2.0	+0.053	3.5
	5	—0.040	2.7	+0.073	*4.9*
	6	—0.046	3.1	+0.087	*5.8*
	7	—0.011	0.7	+0.058	3.8
	8	+0.017	1.1	+0.041	2.7
	9	+0.034	2.3	+0.035	2.3

(3) In view of the fact that we are dealing with only a twelfth of the solar disk at any one time, the frequency with which the correlation coefficients rise to more than four times the probable error would seem to indicate some connection between the electrical conditions of the sun and the earth.

(4) In any given solar longitude the spots in the sun's northern and southern hemispheres generally produce opposite results. That is, if a spot in a given solar longitude in the sun's northern hemisphere strengthens the potential gradient at London by making it more strongly negative, a similar spot in the sun's southern hemisphere usually weakens the gradient. This is the kind of result that would be expected if in any given longitude a spot in one hemisphere sends a predominance of negative electrons to the earth, or to the particular latitude with which we are now dealing, while a spot in the same longitude in the other solar hemisphere sends positive electrons. But when a spot passes from one side of the sun's disk to the other, remaining always in essentially the same lati-

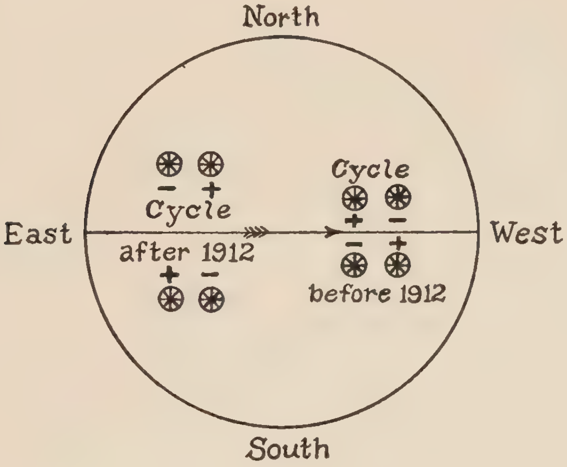

Fig. 34.

Arrangement of Positive and Negative Poles in Sunspots.

tude, its electrical effects, at least in the region of London, appear to change greatly in intensity or even are reversed in quality, so that a spot, or spot group, which increases the negative atmospheric gradient at one time may decrease the gradient or make it more positive at another.

(5) The coefficients for the sun's northern hemisphere show two maxima, one at the time when the areas of the spots were measured (the day marked 0), the other when the spots are within 30° or 40° of the sun's western margin. The coefficients for the southern hemisphere show minima at corresponding times, and also a maximum when the spots first appear on the sun's margin. The resultant symmetry of Fig. 34 is perhaps the most important and certainly the most obvious feature of the present comparison. Since the correlation coefficient between the two lines of Fig. 34 (—0.686) is 8.6 times the probable error, there is only one chance in billions that the two lines accidentally follow such nearly opposite courses.

(6) The effect of the sunspots upon the earth's electrical conditions appears to begin before the spots reach the sun's eastern margin, and may continue after the spots pass the western margin. This suggests that the electronic emissions pursue curved paths, a suggestion which is also in line with the peculiar way in which the whole of Fig. 34 is displaced upward so that the zero line lies below the center of symmetry.

The variation in the apparent effect of sunspots from north to south and east to west seems to require some highly peculiar electrical conditions in the sun. A study of the results obtained by Hale and others at the Mount Wilson Observatory[4] suggests that such conditions actually exist, although this was not known when the preceding conclusions as to sunspots and atmospheric electricity were first formulated. The magnetic conditions of sunspots, as stated by Hale,[5] are briefly as follows:

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[4] G. E. Hale, F. Ellerman, S. B. Nicholson, A. H. Joy: The Magnetic Polarity of Sunspots, Astrophysical Journal, Vol. 49, 1919, pp. 153-178.

> Most sunspots are associated in pairs, of opposite magnetic polarity, in which the preceding (western) spot is usually the larger of the two. 61 per cent of 970 spots examined in the years 1915-1917 were of the bipolar type, while 33 per cent were unipolar. All but 11 per cent of the unipolar spots, however, showed a tendency toward the bipolar type, indicated by trains of calcium flocculi following (less often preceding) the single member. Frequently such groups oscillate between the polar and bipolar types, one or more small spots appearing or disappearing within the mass of calcium flocculi. This peculiarity has led to a search for invisible spots, regarded as vortices giving appreciable magnetic fields, in which the cooling due to expansion is insufficient to cause perceptible darkening of the sun's surface.

The result of this search was that during the winter of 1921-1922 Hale and Ellerman found more than a dozen invisible spots with magnetic fields of 200 to 500 gausses. Some were positive and some negative, and all seemed to be parts of pairs. An examination of earlier magnetic records disclosed

> nine other cases in which a local magnetic field was observed where no spot was recorded. Most of these were probably invisible spots, but as very small spots at the points in question might have escaped notice, and as the magnetic observations were not followed up, they are not included here. The systematic observation of invisible spots, especially during the periods preceding and following the visible life of those that reach maturity, should assist materially in revealing the cause of spot formation.

[5] George E. Hale: Invisible Sunspots, Proc. Nat. Acad. Sci., Vol. 8, 1922, pp. 168-170.

Their frequency of occurrence is probably much greater than these first results suggest.

If invisible spots are really so frequent as Hale implies, it appears as if almost all spots must be bipolar. It also seems probable that parts of the sun may often be magnetically or electrically active without their activity being detected through visible manifestation in sunspots or otherwise, a conclusion reached long ago by Veeder[6] from a study of auroras and barometric variations in the earth's atmosphere.

At any given time, according to Hale, the arrangement of the visible spots, and presumably of those that are invisible, is such that the same pole leads in the great majority, although not in all the pairs in the sun's northern hemisphere, while the other leads in the south. That is, if the negative pole usually appears first when rotation brings a spot into view on the sun's eastern margin in the northern hemisphere, as was the case in the solar cycle which included the years 1904-1909 (see Fig. 34), the positive pole will be the normal leader in the southern hemisphere. Sometimes, however, as will be shown more fully later, the conditions are suddenly reversed so that the leaders are positive where they have been negative, or vice versa. Such an occurrence is reported by the Mount Wilson Observatory in 1912, near sunspot minimum. It is possible that a similar reversal took place about 1896. At any rate, at that time the Lockyers found a reversal of certain characteristics of the sunspot spectrum, including a widening of the iron lines and of some others whose origin is not yet known.

As to the electrical conditions which accompany the bipolar sunspots we have as yet no direct information. In spite of repeated attempts by means of the Stark method no indication of electrical as distinguished from magnetic activities has yet been detected in the sun. But the Stark method gives visible results only in a very strong electrical field. Hence, there may be solar electrical fields of moderate strength. Although they have not yet been observed, their presence seems probable. The sun's magnetic state, as already explained, cannot be due to permanent magnetization, for that is impossible at high temperatures. It is therefore presumably due to electrical currents. Some of these are probably maintained constantly, for the sun appears never to lose its magnetic polarity. Others are presumably temporary. Such temporary currents are the probable cause of the magnetic polarity of sunspots. Such bipolarity might arise from two negative currents moving in opposite directions, from two positive currents moving in opposite directions, or from a negative and a positive current moving in the same direction. The bipolarity would not necessarily cause the emission of different kinds of electrons from the two poles, but the differences in the magnetic fields of the two poles might cause positive and negative electrons to suffer different degrees of deflection, and thus to become more or less separated.

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[6] Ellsworth Huntington: The Geographical Work of Dr. M. A. Veeder, Geog. Rev., Vol. 3, 1917, pp. 188-211 and 303-306.

Without further discussion of these hypothetical matters let us sum up what actually happened from 1904 to 1909, as indicated by the correlation coefficients. In the northern solar hemisphere there were a great many pairs of sunspots with polarities like those shown in the northwest quadrant of Fig. 34. At London, where a latitude of over 50° presumably causes the terrestrial response to be somewhat different from the response at the equator or the poles, the negative leaders of such pairs appear to have had no immediate effect on the electrical potential of the terrestrial atmosphere so long as the spots were close to the sun's eastern margin. Either their effect on atmospheric electricity was delayed several days, or else the earth did not happen to lie within the zone of their influence. Even if electrons were shot off vertically from the radiating surfaces of the spots, they must have been deflected by the general magnetic field of the sun, by the special magnetic field of the spot whence they originated, and by the magnetic field of the earth. Perhaps such deflection prevented the negative spots in the northern solar hemisphere from having any appreciable effect upon atmospheric electricity at London when the spots first appeared on the sun's eastern margin during the period from 1904 to 1909. As the spots came more fully into view, however, their apparent effect increased rapidly. According to both our sets of correlation coefficients, as shown in Figs. 31 and 33, the negative sunspots presumably continued to produce an effect upon the earth's atmospheric potential until the spots almost reached the sun's western margin. Then, as appears in Fig. 33, the effect suddenly disappeared. The course of events thus accords with the fact that as a rule not only is the foremost or western member of a pair of spots the larger, but the seemingly isolated or unipolar spots ''are normally of the same polarity as the preceding members of the bipolar groups in the same hemisphere.'' (Hale.) Hence that particular polarity would be expected to produce the main effect upon the earth's atmosphere almost to the time when the leading spots reach the sun's western margin. But when the leaders of each pair are about to pass beyond the range of vision the following spots of opposite polarity may still be in a position to exert an influence. At London, however, the positive spots in the sun's northern hemisphere which formed the second member of the bipolar pairs from 1904 to 1909 do not seem to have had any appreciable influence on the earth's atmospheric electrical gradient, for only rarely in Table 20 and Fig. 33 do the correlation coefficients of the northern solar hemisphere become negative.

The sun's southern hemisphere from 1904 to 1909 appears to have exerted the same kind of effect as the northern except that the polarity was of an opposite type. It should be noted, however, that the center of symmetry of Fig. 33 is not on the zero line, but at a correlation coefficient of about 0.025. This perhaps corresponds with the fact that London lies in a high northern latitude. Disregarding this, it seems that when spots first appeared on the eastern margin of the sun's southern hemisphere their positive leaders did not influence the earth's atmosphere at London or else their effect was delayed. On the other hand, the negative spots seem to have had an important effect, as appears in the high positive values near the left end of the dotted line in Fig. 33. As the spots crossed the solar disk the positive leaders appear gradually to have become effective, just as did the negative leaders in the other hemisphere. At every longitude, not only while spots are on the sun's visible disk, but even when they are behind the sun, the apparent tendency of the spots in the northern hemisphere is toward an effect opposite to that of spots in the southern hemisphere.

Here we must leave the matter. The net result of the present chapter seems to be that a large body of evidence indicates a close relation between the earth's atmospheric electricity, and the position and magnetic polarity of sunspots. How this relationship comes about we do not yet know. For the present we are concerned only with finding out the facts. If they are known an explanation will be forthcoming in due time.

CHAPTER VIII

A POSSIBLE ELECTRICAL FACTOR IN BAROMETRIC PRESSURE

THE problem before us in this chapter is whether the sun's electrical activity, working presumably through the electrical potential of the earth's atmosphere, has any appreciable effect upon atmospheric pressure and thus upon other meteorological phenomena. The solution of this problem is difficult. That atmospheric electricity has some effect upon atmospheric pressure is generally agreed, but whether that effect is large enough to be of any appreciable significance in producing changes of weather is not clear. The reason for uncertainty is that two separate lines of evidence seem to lead to opposite conclusions. On the one hand, a mathematical analysis of the relation between atmospheric electricity and atmospheric pressure seems to make an electrical hypothesis of the weather untenable. On the other hand, the actual facts of observation suggest that atmospheric pressure is related to the sun's electrical activity quite as closely as is atmospheric electricity.

In order that all sides of this complex problem may be treated adequately, we shall begin with a clear and concise mathematical analysis by Humphreys in which he shows that if his assumptions are correct, an electrical hypothesis is of no appreciable importance in meteorology. Next we shall consider the actual facts during the years 1904 to 1909, and shall see that they apparently point to a real and important relationship between the sun's electrical activity and the earth's atmospheric pressure. We shall then be confronted by the necessity of choosing between the mathematical analysis and the facts of observation. The complete statement by Humphreys is as follows:[1]

> It has been suggested that many cyclones and anticyclones may be caused by changes in the electrification of the outer atmosphere, such changes, for instance, as presumably occur at the times of brilliant auroræ. It is proposed to check this suggestion by a simple calculation.
>
> Let any considerable, more or less circular, horizontal extent of the upper air be uniformly electrified to the equivalent of a surface charge of density ρ units of electricity per square centimeter, and let the earth immediately beneath have an equal charge of opposite sign.
>
> Now, if there is no other disturbing electrification, the force f on a unit quantity of electricity anywhere between the earth and air charges (assuming, as is approximately true, that the direction of the electric force is everywhere vertical) is given by the well-known equation
>
> $$f=4\pi\rho$$
>
> of which half is from the air charge and half from the earth charge.
>
> Hence the total electrical pull P between the air and the earth is given by the expression
>
> $$P=2\pi\rho^2 A \tag{1}$$
>
> in which A is the area of the charged surface of the earth.
>
> From the value of f, it follows that the work w necessary to carry a unit charge through a difference of level h within the full electric field is
>
> $$w=4\pi\rho h,$$

---

[1] W. J. Humphreys: The Electrical Charge of the Atmosphere and the Height of the Barometer, Mo. Weath. Rev., Vol. 49, No. 10, 1921.

or, substituting for ρ its value in terms of P and A, equation (1),

$$w=4\pi h\sqrt{\frac{P}{2\pi A}}.$$

Hence

$$\left(\frac{w}{h}\right)^2=8\pi\frac{P}{A}=8\pi p \qquad (2)$$

where p=dynes pull on each square centimeter of the electrified surface of the earth, or upper air.

But w/h=ergs work on an electrostatic unit of electricity per its centimeter change in level.

Now, the normal vertical potential difference in the atmosphere is about one volt per centimeter. Hence, converting to electrostatic units, and substituting in (2),

$$\left(\frac{1}{300}\right)^2=8\pi p,$$

or

$$p=1/2{,}261{,}947.$$

But the weight of one cubic centimeter of mercury at 0°C., and under normal gravity

$$=13.5951\times 980.665 \text{ dynes}$$
$$=13{,}332.24 \text{ dynes.}$$

Hence p equals the weight of a column of mercury 1 square centimeter in cross section and 1/30,156,820,271 centimeter, or, say $1/(3\times 10^9)$ millimeter, high.

That is, a local electrification of the outer atmosphere sufficient to produce a potential difference between it and the earth, having an equal charge of opposite sign, of 1 volt per centimeter difference in level would increase the height of the mercurial barometer about $1/(3\times 10^9)$ millimeter.

If, however, the outer atmosphere were charged to this extent over all the earth, each square centimeter of it (regarded as a charged surface) would be repelled radially outward by the rest of the charge on the shell with the force F given, as is well known, by the equation

$$F=4\pi\rho^2.$$

Hence, from (1), per square centimeter of the charged surface,

$$F=2P.$$

That is, if the upper air is charged to the extent supposed, all around the earth, the mercurial barometer will stand *lower* by the same amount it would stand *higher* in response to an equally dense local charge, namely, in the present case, by $1/(3\times10^9)$ millimeter.

But, as an extreme case, let the charge be local, as first assumed, and let the potential difference with change of elevation be 30,000 volts per centimeter, a value far in excess of any observed except occasionally, perhaps, during the passage of a thunderstorm. With this extreme local electrification the barometer would be raised only about 3/10 millimeter.

Obviously, therefore, no appreciable portion of those considerable changes in atmospheric pressure, giving differences in the readings of the barometer of, say, 2 to 3 centimeters, characteristic of the passage of cyclones and anticyclones, can logically be attributed to variations in the electrification of the upper air, whether at the times of auroras or at any other time. Hence, it seems extremely improbable that either cyclones or anticyclones are ever produced by changes in the electrification of the outer atmosphere.

Let us now turn to certain facts of observation which suggest that in spite of the quantitative difficulty of the problem, the barometric conditions of the earth's atmosphere bear a relationship to the sun's electrical condition. In Chapter III we found that the barometric gradients over the North Atlantic Ocean show a peculiar relation to sunspots. In a general way the gradients are high when the number of sunspots is great. Spots in the center of the solar disk, however, are associated with relatively low gradients, while those on the margins are associated with strong gradients. This agrees with a conclusion announced by Veeder long ago to the effect that both auroras and storms are especially influenced by disturbances near the margins of the sun's disk. Clayton[2] has recently verified this conclusion so fully that it seems scarcely open to question. Further analysis, as given in Chapter III, shows that the highest gradients occur not merely when there are many spots on the solar margins, but when there is a great excess in one or the other of the two pairs of marginal quadrants whose members lie diagonally opposite to one another. In other words, from 1904 to 1909 the terrestrial barometric gradients over the North Atlantic Ocean were highest when the combined area of sunspots in the northeast and southwest quadrants of the solar disk showed a maximum difference from the combined area of the similar spots in the northwest and southeast quadrants. This apparently means that spots in the northeast and southwest quadrants have an opposite effect from those in the northwest and southeast quadrants. Such an effect is impossible on the hypothesis of a purely thermal control of the weather, but now that the bipolarity of sunspots has been demonstrated, it appears to be in harmony with an electrical hypothesis.

The only way to arrive at any correct conclusion in this matter is to obtain more facts. Accordingly let us investigate the relation between sunspots and barometric gradients, using the method employed in the last chapter for the relationship between sunspots and the atmospheric potential gradients at Kew. For the barometric gradients the daily data for the northern half of the North Atlantic Ocean and the adjoining lands have been used for the years 1904 to 1909, the material being that which was employed in Chapter III. For the sun the spots in the northwest and southwest quadrants have been chosen, since those two quadrants are the ones where sunspots show the strongest relation to the potential gradients of atmospheric electricity at Kew. The method of comparison has been that of correlation coefficients, exactly as in the preceding chapter. Coefficients have been obtained between the solar conditions of any given day and the barometric conditions of that day and the nine succeeding days. The results appear in Table 21, where the coefficients for each of the twelve months, and for periods of three months, six months, and a year are given.

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[2] H. H. Clayton: World Weather, New York, 1923, pp. 290-300.

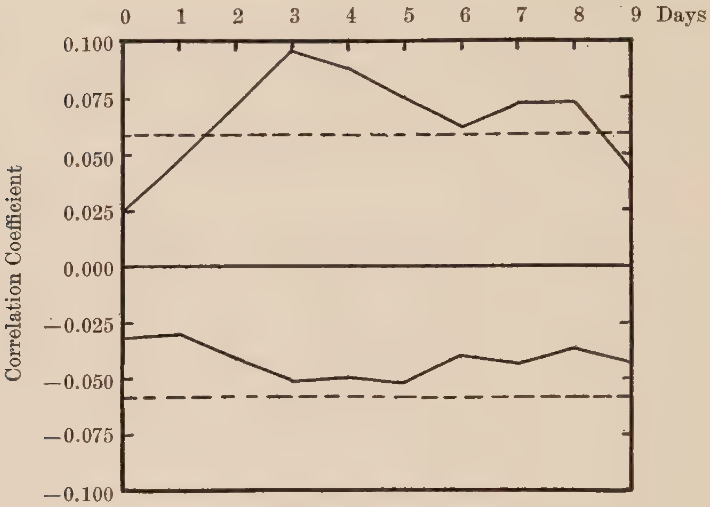

Fig. 35.

Contrasted Correlation Coefficients of Northern (below) and Southern Sunspots (above) when compared with Daily Barometric Gradients over the Northern Part of the North Atlantic Ocean, 1904-1909.

TABLE 21

SUMMARY OF CORRELATION COEFFICIENTS BETWEEN SUNSPOTS AND BAROMETRIC GRADIENTS OVER NORTHERN PART OF NORTH ATLANTIC OCEAN, 1904-1909

A. NORTHWEST SOLAR QUADRANT BY MONTHS AND FOR THE WHOLE YEAR

Coefficients more than 3 times the probable error are indicated by the use of italic figures, thus (*—0.202*); more than 4 times by the use of large black type, thus (**—0.214**).

	0	*1*	*2*	*3*	*4*	*5*	*6*	*7*	*8*	*9*	*Probable error*	*Ratio of maximum coefficient to its probable error*
Jan.	+0.005	—0.071	—0.110	—0.105	—0.128	—0.111	—0.078	+0.005	+0.085	+0.182	±0.054 to ±0.053	2.4
Feb.	—0.167	**—0.214**	**—0.323**	**—0.278**	*—0.202*	—0.058	+0.015	+0.081	+0.153	+0.083	±0.056 to ±0.051	6.1
Mar.	—0.006	+0.001	+0.040	+0.013	+0.003	—0.021	—0.026	—0.088	**—0.201**	**—0.218**	±0.050 to ±0.048	4.5
Apr.	—0.123	—0.080	—0.076	—0.059	—0.066	—0.102	—0.151	*—0.188*	*—0.176*	**—0.200**	±0.050 to ±0.048	4.2
May	**—0.224**	—0.121	—0.137	*—0.185*	*—0.181*	**—0.225**	*—0.195*	*—0.180*	**—0.230**	**—0.206**	±0.050 to ±0.048	4.8
June	*—0.184*	—0.140	—0.090	—0.150	*—0.169*	—0.104	—0.068	—0.100	—0.085	—0.108	±0.050 to ±0.048	3.8
July	—0.138	*—0.163*	**—0.213**	**—0.220**	**—0.239**	**—0.320**	**—0.311**	**—0.247**	—0.141	—0.049	±0.050 to ±0.045	7.1
Aug.	—0.097	—0.139	*—0.183*	—0.134	—0.110	—0.062	—0.091	—0.120	—0.120	—0.149	±0.050 to ±0.048	3.8
Sept.	+0.105	**+0.219**	**+0.284**	**+0.334**	**+0.340**	**+0.299**	**+0.241**	+0.122	+0.052	+0.066	±0.050 to ±0.045	7.6
Oct.	*—0.176*	*—0.176*	*—0.183*	**—0.226**	**—0.224**	*—0.188*	—0.139	—0.136	—0.115	—0.146	±0.050 to ±0.047	4.8
Nov.	**+0.212**	**—0.242**	*+0.178*	+0.128	+0.117	+0.105	+0.089	+0.039	+0.042	+0.055	±0.050 to ±0.047	5.1
Dec.	+0.032	+0.009	+0.059	+0.032	+0.036	+0.004	+0.038	+0.090	+0.098	+0.072	±0.050 to ±0.049	2.0
Year	—0.032	—0.030	—0.041	*—0.051*	*—0.050*	*—0.051*	—0.041	—0.044	—0.037	—0.044	±0.0146 to ±0.0146	3.5

(Continued on next page)

TABLE 21 (Continued)

B. SOUTHWEST SOLAR QUADRANT BY MONTHS AND FOR THE WHOLE YEAR

	0	*1*	*2*	*3*	*4*	*5*	*6*	*7*	*8*	*9*	*Probable error*	*Ratio of maximum coefficient to its probable error*
Jan.	—0.160	**—0.207**	*—0.165*	—0.127	—0.134	—0.159	—0.147	—0.081	—0.074	—0.039	±0.054 to ±0.052	4.0
Feb.	—0.007	+0.060	+0.104	*+0.164*	+0.119	+0.111	+0.109	+0.102	+0.058	+0.011	±0.056 to ±0.054	3.0
Mar.	—0.097	—0.053	—0.010	+0.055	+0.092	+0.086	+0.141	*+0.167*	**+0.202**	+0.143	±0.050 to ±0.048	4.2
Apr.	—0.090	—0.079	—0.083	0.000	+0.032	+0.041	+0.048	+0.043	+0.028	—0.020	±0.050 to ±0.050	1.8
May	+0.026	+0.007	+0.022	+0.025	—0.018	—0.061	—0.104	—0.096	—0.039	+0.027	±0.050 to ±0.049	2.1
June	—0.032	+0.049	+0.143	*+0.178*	**+0.203**	**+0.252**	**+0.248**	**+0.210**	+0.124	+0.070	±0.050 to ±0.047	5.3
July	**—0.219**	**—0.278**	**—0.286**	*—0.190*	—0.141	*—0.176*	—0.112	—0.075	—0.083	—0.153	±0.050 to ±0.046	6.0
Aug.	*—0.187*	*—0.182*	—0.144	—0.134	—0.085	—0.104	—0.114	—0.068	+0.007	+0.082	±0.050 to ±0.048	3.9
Sept.	**+0.266**	**+0.233**	**+0.219**	**+0.213**	+0.094	+0.100	+0.100	+0.120	*+0.177*	+0.141	±0.050 to ±0.047	5.0
Oct.	**+0.488**	**+0.502**	**+0.537**	**+0.526**	**+0.517**	**+0.439**	**+0.373**	**+0.357**	**+0.328**	**+0.255**	±0.050 to ±0.035	15.3
Nov.	**+0.198**	**+0.215**	**+0.199**	+0.145	+0.094	+0.134	+0.102	+0.015	—0.059	—0.057	±0.050 to ±0.048	4.5
Dec.	+0.066	+0.097	+0.100	+0.091	+0.143	+0.116	+0.031	+0.042	+0.082	—0.049	±0.050 to ±0.049	2.9
Year	+0.025	*+0.048*	**+0.072**	**+0.096**	**+0.089**	**+0.075**	**+0.062**	**+0.073**	**+0.073**	+0.043	±0.0146 to ±0.0145	6.9

TABLE 21 (Continued)

C. NORTHWEST SOLAR QUADRANT BY PERIODS OF THREE MONTHS

	0	*1*	*2*	*3*	*4*	*5*	*6*	*7*	*8*	*9*	*Probable error*	*Ratio of maximum coefficient to its probable error*
Jan.-Mar.	—0.039	—0.071	*—0.094*	—0.093	—0.087	—0.055	—0.034	—0.007	+0.000	+0.014	±0.031 to ±0.031	3.0
Feb.-Apr.	—0.084	—0.087	*—0.104*	—0.087	—0.078	—0.048	—0.038	—0.054	—0.079	*—0.111*	±0.031 to ±0.030	3.7
Mar.-May	*—0.101*	—0.055	—0.042	—0.064	—0.069	*—0.099*	*—0.104*	**—0.132**	**—0.192**	**—0.194**	±0.029 to ±0.028	6.9
Apr.-June	*—0.155*	*—0.113*	*—0.104*	**—0.135**	**—0.140**	**—0.147**	**—0.140**	**—0.150**	**—0.161**	**—0.168**	±0.029 to ±0.028	6.0
May-July	**—0.161**	**—0.133**	**—0.147**	**—0.176**	**—0.188**	**—0.222**	**—0.200**	**—0.174**	**—0.143**	*—0.105*	±0.029 to ±0.028	7.9
June-Aug.	**—0.125**	**—0.138**	**—0.160**	**—0.164**	**—0.170**	**—0.179**	**—0.171**	**—0.158**	*—0.109*	—0.086	±0.029 to ±0.028	6.4
July-Sept.	—0.037	—0.044	—0.018	+0.011	+0.013	—0.020	—0.040	—0.067	—0.054	—0.023	±0.029 to ±0.029	2.3
Aug.-Oct.	—0.061	—0.032	—0.020	—0.005	+0.005	+0.016	+0.010	—0.039	—0.054	—0.055	±0.029 to ±0.029	2.1
Sept.-Nov.	+0.051	*+0.091*	+0.083	+0.068	+0.066	+0.063	+0.057	+0.005	—0.007	—0.049	±0.029 to ±0.029	3.1
Oct.-Dec.	+0.041	+0.035	+0.024	—0.017	—0.020	—0.021	—0.000	—0.005	+0.005	—0.051	±0.029 to ±0.029	1.8
Nov.-Jan.	*+0.104*	*+0.110*	+0.018	+0.028	+0.020	+0.009	+0.022	+0.041	+0.066	+0.053	±0.029 to ±0.029	3.8
Dec.-Feb.	—0.018	—0.077	*—0.104*	*—0.101*	—0.084	—0.055	—0.012	+0.054	*+0.104*	*+0.117*	±0.029 to ±0.029	4.0

(Continued on next page)

TABLE 21 (Continued)

D. SOUTHWEST SOLAR QUADRANT BY PERIODS OF THREE MONTHS

	0	*1*	*2*	*3*	*4*	*5*	*6*	*7*	*8*	*9*	*Probable error*	*Ratio of maximum coefficient to its probable error*
Jan.-Mar.	—0.050	—0.020	+0.017	+0.067	+0.050	+0.038	+0.050	+0.063	+0.051	+0.025	±0.031 to ±0.031	2.2
Feb.-Apr.	—0.039	+0.005	+0.033	*+0.093*	+0.082	+0.076	+0.087	+0.088	+0.071	+0.028	±0.031 to ±0.030	3.1
Mar.-May	—0.052	—0.040	—0.023	+0.027	+0.036	+0.024	+0.032	+0.042	+0.064	+0.047	±0.029 to ±0.029	2.2
Apr.-June	—0.029	+0.005	+0.029	+0.068	+0.074	+0.080	+0.063	+0.052	+0.037	+0.022	±0.029 to ±0.029	2.8
May-July	—0.063	—0.063	—0.028	+0.014	+0.024	+0.017	+0.017	+0.019	+0.006	—0.012	±0.029 to ±0.029	2.2
June-Aug.	**—0.141**	**—0.135**	*—0.091*	—0.051	—0.009	—0.010	—0.001	+0.015	+0.013	+0.013	±0.029 to ±0.028	5.0
July-Sept.	—0.037	—0.044	—0.033	—0.007	—0.024	—0.035	—0.026	+0.008	+0.057	+0.053	±0.029 to ±0.029	2.0
Aug.-Oct.	**+0.172**	**+0.202**	**+0.224**	**+0.220**	**+0.191**	**+0.160**	**+0.133**	**+0.148**	**+0.184**	**+0.167**	±0.029 to ±0.028	8.0
Sept.-Nov.	**+0.277**	**+0.306**	**+0.313**	**+0.298**	**+0.228**	**+0.220**	**+0.191**	**+0.177**	**+0.176**	**+0.136**	±0.029 to ±0.027	11.6
Oct.-Dec.	**+0.249**	**+0.290**	**+0.302**	**+0.281**	**+0.284**	**+0.297**	**+0.187**	**+0.172**	**+0.156**	+0.080	±0.029 to ±0.027	11.2
Nov.-Jan.	+0.022	+0.024	+0.032	+0.029	+0.036	+0.021	—0.012	—0.000	—0.005	—0.045	±0.029 to ±0.029	1.6
Dec.-Feb.	—0.017	+0.014	+0.041	+0.074	+0.063	+0.044	+0.029	+0.044	+0.031	—0.013	±0.029 to ±0.029	2.5

TABLE 21 (Continued)

E. Northwest Solar Quadrant by Periods of Six Months

	0	*1*	*2*	*3*	*4*	*5*	*6*	*7*	*8*	*9*	*Probable error*	*Ratio of maximum coefficient to its probable error*
Jan.-June	**—0.094**	**—0.092**	**—0.107**	**—0.115**	**—0.113**	**—0.093**	*—0.078*	—0.061	—0.060	—0.053	±0.021 to ±0.021	5.5*
Feb.-July	**—0.121**	**—0.108**	**—0.123**	**—0.135**	**—0.131**	**—0.133**	**—0.117**	**—0.111**	**—0.106**	**—0.104**	±0.021 to ±0.021	6.4*
Mar.-Aug.	**—0.111**	**—0.095**	**—0.101**	**—0.113**	**—0.117**	**—0.137**	**—0.134**	**—0.142**	**—0.147**	**—0.138**	±0.021 to ±0.021	7.0*
Apr.-Sept.	**—0.087**	—0.050	—0.048	—0.042	—0.042	—0.065	*—0.074*	**—0.094**	**—0.091**	*—0.074*	±0.021 to ±0.021	4.5*
May-Oct.	**—0.107**	*—0.078*	*—0.079*	**—0.084**	**—0.084**	**—0.093**	**—0.086**	**—0.100**	**—0.094**	*—0.083*	±0.021 to ±0.021	5.1*
June-Nov.	—0.019	+0.001	—0.012	—0.023	—0.026	—0.031	—0.029	—0.056	—0.045	*—0.063*	±0.021 to ±0.021	3.0*
July-Dec.	+0.008	+0.013	+0.005	+0.005	—0.006	—0.021	—0.018	—0.032	—0.021	—0.038	±0.021 to ±0.021	1.3*
Aug.-Jan.	+0.031	+0.028	+0.021	+0.023	+0.011	+0.012	+0.017	+0.006	+0.014	+0.001	±0.021 to ±0.021	1.1
Sept.-Feb.	+0.020	+0.016	+0.001	+0.003	—0.002	+0.010	+0.026	+0.026	+0.041	+0.023	±0.021 to ±0.021	1.4
Oct.-Mar.	+0.004	—0.017	—0.037	—0.049	—0.057	—0.041	—0.016	—0.007	+0.003	—0.021	±0.021 to ±0.021	2.7*
Nov.-Apr.	+0.032	+0.013	—0.008	—0.010	—0.005	—0.013	—0.002	+0.004	—0.004	—0.012	±0.021 to ±0.021	1.5
Dec.-May	—0.054	*—0.068*	*—0.077*	*—0.073*	*—0.080*	*—0.074*	—0.055	—0.030	—0.047	—0.025	±0.021 to ±0.021	3.8*

(Continued on next page)

TABLE 21 (Continued)

F. SOUTHWEST SOLAR QUADRANT BY PERIODS OF SIX MONTHS

	0	*1*	*2*	*3*	*4*	*5*	*6*	*7*	*8*	*9*	*Probable error*	*Ratio of maximum coefficient to its probable error*
Jan.-June	—0.042	—0.013	+0.022	+*0.066*	+0.058	+0.053	+0.054	+0.059	+0.046	+0.024	±0.021 to ±0.021	3.1
Feb.-July	—0.050	—0.022	+0.012	+*0.063*	+0.061	+0.055	+0.062	+*0.063*	+0.048	+0.014	±0.021 to ±0.021	3.0
Mar.-Aug.	**—0.099**	**—0.087**	—0.057	—0.014	+0.012	+0.006	+0.014	+0.027	+0.040	+0.029	±0.021 to ±0.021	4.8*
Apr.-Sept.	—0.033	—0.026	—0.005	+0.026	+0.019	+0.015	+0.015	+0.027	+0.046	+0.038	±0.021 to ±0.021	2.2
May-Oct.	+*0.069*	**+0.090**	**+0.118**	**+0.132**	**+0.119**	**+0.099**	**+0.085**	**+0.094**	**+0.110**	**+0.093**	±0.021 to ±0.021	6.3
June-Nov.	**+0.085**	**+0.109**	**+0.133**	**+0.142**	**+0.131**	**+0.119**	**+0.106**	**+0.106**	**+0.107**	**+0.083**	±0.021 to ±0.021	6.8
July-Dec.	**+0.100**	**+0.116**	**+0.127**	**+0.129**	**+0.122**	**+0.099**	+*0.077*	**+0.085**	**+0.102**	**+0.098**	±0.021 to ±0.021	5.9
Aug.-Jan.	**+0.111**	**+0.117**	**+0.132**	**+0.128**	**+0.116**	**+0.095**	+*0.067*	**+0.080**	**+0.097**	**+0.105**	±0.021 to ±0.021	6.3
Sept.-Feb.	**+0.109**	**+0.140**	**+0.154**	**+0.171**	**+0.141**	**+0.121**	**+0.100**	**+0.102**	**+0.087**	+*0.079*	±0.021 to ±0.020	8.6
Oct.-Mar.	+*0.071*	**+0.105**	**+0.132**	**+0.151**	**+0.144**	**+0.122**	**+0.105**	**+0.107**	**+0.093**	+*0.475*	±0.021 to ±0.020	7.6
Nov.-Apr.	—0.015	+0.012	+0.032	+0.061	+*0.063*	+0.054	+0.049	+0.053	+0.042	+0.030	±0.021 to ±0.021	3.0
Dec.-May	—0.028	—0.005	+0.018	+0.051	+0.052	+0.036	+0.029	+0.042	+0.043	+0.037	±0.021 to ±0.021	2.5

The yearly coefficients of Table 21 are shown graphically in Fig. 35. There it appears that for the two thousand days of the six years from 1904 to 1909 the correlation coefficients between barometric gradients and the sunspots in the northwestern and southwestern solar quadrants are systematically opposite in sign. Moreover, the spots in the northern solar hemisphere have negative coefficients, which means that they are associated with gentle barometric gradients. The spots in the southern solar hemisphere are correlated with high barometric gradients, and hence appear to be related to low atmospheric pressure and storms. On seven out of ten days the coefficients for the southern hemisphere, Section B of Table 21, are more than four times the probable error, while on the third and fourth days after a given degree of spottedness the coefficients are more than six times the probable error. Even though these coefficients are absolutely small, the largest being only +.096, the fact that we are dealing with only one-fourth of the sun's area, and that there are many other factors both terrestrial and solar which tend to reduce the correlation, makes them significant. It should be noted that they are based on over 2000 days. Moreover, they rise regularly from +.025 on the day of observation to nearly four times as much on the fourth day thereafter, and then decline with almost equal regularity, the value on the ninth day being +.043. The coefficients for the northern solar hemisphere, Section A of Table 21, are neither so large nor so regular as those for the southern. Nevertheless, the mere fact that they are all negative while those of the northern hemisphere are all positive can scarcely be accidental. Moreover, the fact that three successive coefficients on the third, fourth, and fifth days are each more than three times the probable error, appears to be significant, inasmuch as only one of the four solar quadrants is taken into account.

In spite of all these considerations, the reader may feel that coefficients ranging only from .05 to .10 cannot be very important. An analysis by months shows that in reality the coefficients are much larger than this, for they vary greatly from season to season. In the southern hemisphere the highest individual coefficient is +.537 in October on the second day after a given solar condition. This is 15.3 times the probable error. Every one of the ten days in the October section of the table for the southwest quadrant by months has a coefficient at least five times the probable error. The largest negative coefficient for the southern solar hemisphere is —.286 in July on the second day. Since this is 6.0 times the probable error, we are confronted by the puzzling condition of both negative and positive correlation coefficients so large that they presumably must indicate a real relationship. For the northern hemisphere the coefficients are of about the same order of magnitude as for the southern, and are equally puzzling because of the variations in their signs. The largest positive coefficient is +.340 (7.6 times the probable error) on the fourth day after a given solar condition in September, while the largest negative coefficient is —.323 (6.1 times its probable error) on the second day after the solar condition in February. July has a negative coefficient, —.320, which is almost as large as that of February, and which bears a higher ratio (7.1) to the probable error, for the error here is smaller than in January and February, where data as to barometric gradients in 1904 are missing. The significance of these high ratios may be judged by turning back to page 28 where it will be seen that for most of them there is not one chance in billions that they are accidental.

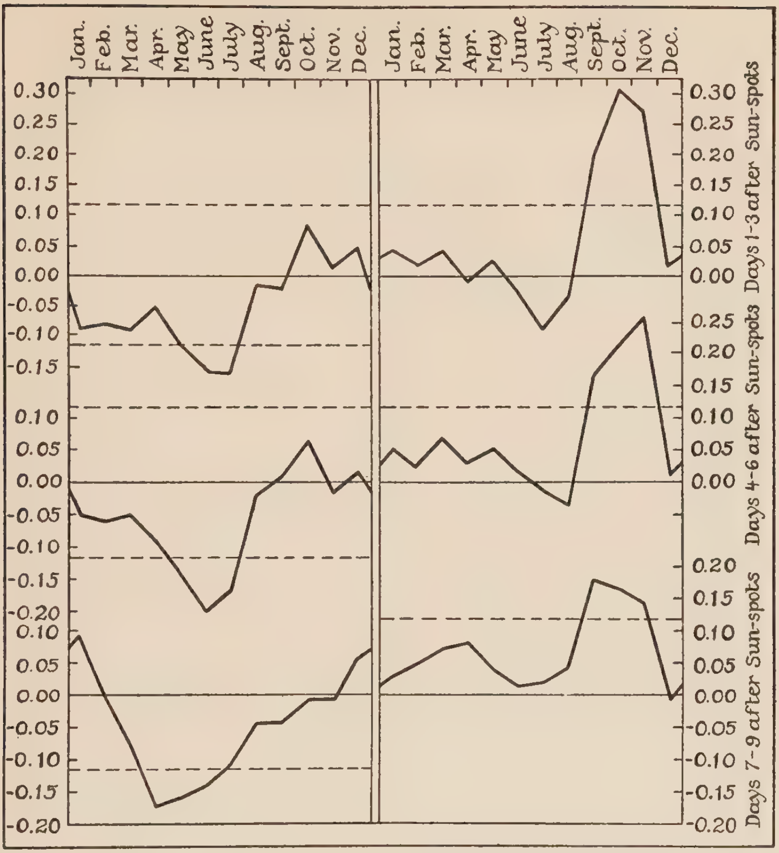

Fig. 36.

Monthly Variations in Correlation Coefficients between Sunspots and Barometric Gradients over Northern Part of North Atlantic Ocean, 1904-1909.

The same barometric data are used in both halves of this diagram, but on the left they are compared with spots in the northwestern solar quadrant, and on the right with spots in the southwestern quadrant. The coefficients are calculated for overlapping periods of three months, and are plotted in the central month. The averages for periods of three successive days are here given. The dash lines denote four times the probable error.

In order to gain light on the peculiar conditions of positive and negative correlations set forth above, I have computed the correlation coefficients by overlapping periods of three months (January to March, February to April, etc.) and of six months (January to June, February to July, etc.), as appears in Table 21. The coefficients for three months are the most significant, since they eliminate the minor variations from month to month and yet permit the seasonal trend to appear clearly. These are used in Fig. 36, where the coefficient for each period of three months is plotted in the middle month. The seasonal trend of the coefficients is shown by lines representing the average coefficients for successive three-day periods after a given solar condition. From the dotted lines it is easy to determine the periods when the average coefficients were more than four times the probable error for a single coefficient. The probable error for a three-day period is less than this. From about the first of April to the end of July the spots in the sun's northern hemisphere display a significant relationship to barometric gradients, while from early September to the end of November the spots in the southern hemisphere display a still more pronounced relationship. During the rest of the year the coefficients are rarely more than twice the probable error and hence may be ignored.

In Fig. 37 the two curves for days 1-3 of Fig. 36 have been placed in juxtaposition. The other curves might have been used almost equally well. One of the noteworthy features of Fig. 37 is the general parallelism of the two curves, a parallelism which gives a correlation coefficient of +.71 (±.11). The reason why the two curves thus run together is apparently that when spots are numerous in one solar hemisphere, they are likely to be numerous in the other also. In a month like January the fact that neither solar hemisphere shows any significant correlation with barometric gradients, probably indicates that although sunspots on both sides of the sun's equator

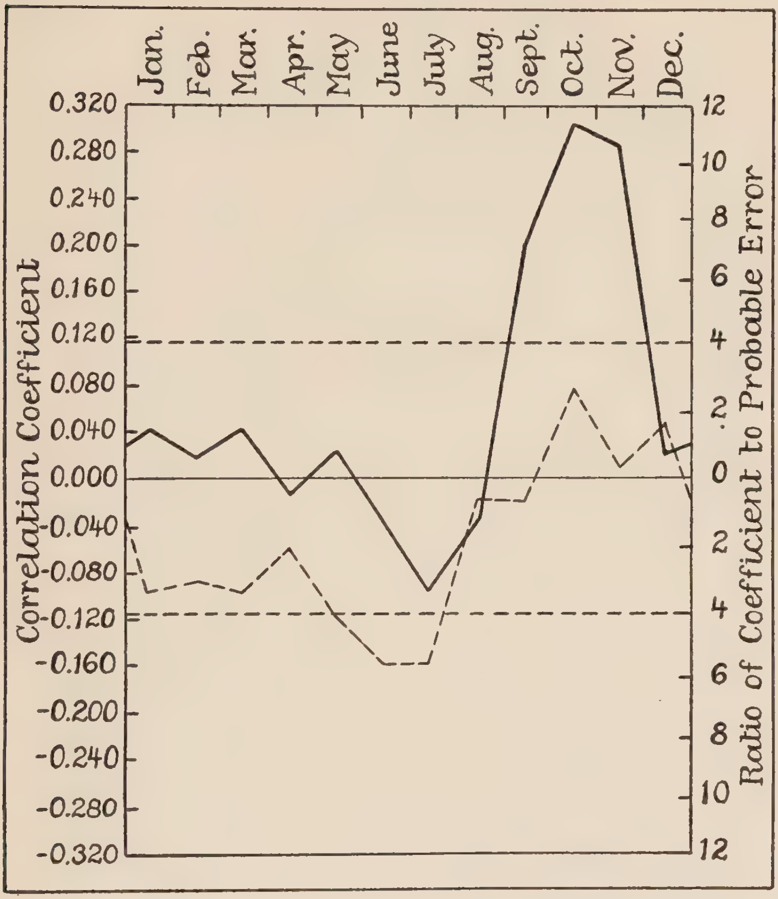

Fig. 37.

Seasonal Contrast between the Relation of Barometric Gradients over the North Atlantic Ocean to Sunspots in the Sun's Northern Hemisphere (dotted line) and Southern Hemisphere (solid line).

The curves here given are the two curves for days 1 to 3 in Fig. 36.

may have a terrestrial effect, the relative positions of the sun and earth and the inclinations of their axes are such that when a considerable period such as six years is considered, the effects of the two hemispheres balance one another. On any given day, however, there is probably no such balance, and hence the varying size, position, and intensity of the sunspots presumably influence the weather. In March, as appears in the lower curve of Fig. 36, the sun's northern hemisphere has begun to have more effect than the southern hemisphere, and by the middle of April the effect has grown so strong that the lowest point of the curve indicates a correlation coefficient more than five times the probable error. This relationship soon rises to about seven times the probable error, as appears in the middle curve. It is maintained till about the end of July, and becomes so strong that it apparently causes the spots in the sun's southern hemisphere to appear to have a slight negative correlation like that of the spots in the northern solar hemisphere. This presumably means merely that although the southern spots have relatively little effect at this season, they are numerous as a rule when the northern spots are numerous. Hence they show an apparent tendency to be associated with low barometric gradients, just as are the northern spots.

It is not easy to determine why the northern spots show their maximum relationship from March to July. In June the earth's northern hemisphere is turned toward the sun, but it would seem as if this would give the southern solar hemisphere as much chance as the northern to exert an unusual effect on the earth. Moreover, the maximum relationship between the northern spots and the barometric gradients seems to come somewhat before the summer solstice instead of lagging behind it. On March 8 the sun's southern pole is turned about 7° toward the earth, for the sun's axis as well as the earth's is inclined to the plane of the earth's orbit. Perhaps this has something to do with the matter. By August the earth and sun are in such positions that the spots in the two solar hemispheres apparently have an equal effect on barometric gradients, and thus the effect of each is neutralized and the correlation coefficients are practically zero.

Next the sun's southern hemisphere with its positive correlation becomes effective, its maximum coefficient, nearly twelve times the probable error (Fig. 37), comes not far from October. The effect of the southern spots is apparently so great that it causes the northern coefficients likewise to be slightly positive. The largest coefficients follow the date, September 8, when the sun's northern pole is most inclined toward the earth. By the time the winter solstice is reached and the earth's southern hemisphere is most inclined toward the sun, the positive relationship of the sun's southern hemisphere has disappeared. At this season, much more than in the spring, it looks as if the inclination of the earth's own axis could not be the controlling factor in determining which solar hemisphere is most closely related to barometric gradients. If the inclination of the sun's axis is the chief factor, it looks as if the solar hemisphere which is turned *away* from the earth were the one that produces the greater effect at any given season. Since the inclination is only about 7° 15′ at most, and since electrons are bound to be deflected by magnetic fields, this is not impossible. Taking the year as a whole, the southern solar hemisphere apparently has a closer relation than the northern to barometric gradients over the Atlantic. Possibly this has something to do with the magnetic polarity of the sun as a whole.

The correlation coefficients of Table 21 suggest many other lines of study. One of these is the amount of lag between the solar cause and its supposed terrestrial effect. In Fig. 35 the line for the sun's northern hemisphere shows a broad minimum from the third to the fifth day and a minor minimum on the seventh day. These perhaps correspond to the two maxima of the northern line in Fig. 33, where the relation of sunspots to atmospheric electricity is illustrated. If so, the main barometric response to solar activity is delayed about four days after the electrical response. The line for the southern solar hemisphere in Fig. 35 shows two maxima, one being three days after the day when the sunspots were observed, while a second but less important maximum occurs on the seventh and eighth days. These perhaps correspond to the minima of the corresponding line in Fig. 33 but with a lag of two or three days after the electrical phenomena. When allowance is made for the fact that the curves of Figs. 33 and 35 are reversed in phase, the electrical relationship appears to show its maximum results only a little after its apparent solar cause, perhaps not as much as a day; while the barometric gradients show a longer lag of from two to four days.

An important question which needs answer at this point is whether the real relation between sunspots, atmospheric electricity, and barometric pressure may not be as follows:—solar activity is associated with variations in ordinary radiation; these alter the earth's temperature; the differences in temperature give rise to convection and to changes in barometric pressure; and the convectional and barometric conditions lead to variations in atmospheric electricity. In this connection it is important to discover the degree to which any one of these associated phenomena lags after the others. We have already seen that, so far as can be judged from the correlation coeffi-

TABLE 22, SECTION A

CORRELATION COEFFICIENTS BETWEEN DAILY ELECTRICAL POTENTIAL AT KEW (DAY 0) AND BAROMETRIC GRADIENTS OVER NORTHERN PART OF NORTH ATLANTIC OCEAN (DAYS —3 TO 5), 1904-1909

	Day —3	*Day —2*	*Day —1*	*Day 0*	*Day 1*	*Day 2*	*Day 3*	*Day 4*	*Day 5*	*Probable error of highest coefficient*
Jan.	—0.129	—0.112	—0.236	—0.300	—0.226	—0.121	—0.162	—0.227	—0.205	±0.051
Feb.	+0.009	—0.089	—0.162	—0.252	—0.137	—0.138	—0.180	—0.110	—0.121	±0.052
Mar.	—0.133	—0.064	—0.127	—0.221	—0.189	—0.167	—0.106	—0.145	—0.114	±0.050
Apr.	—0.134	—0.081	—0.095	—0.116	—0.182	—0.107	—0.144	—0.238	—0.129	±0.050
May	—0.113	—0.126	—0.180	—0.224	—0.186	—0.161	—0.210	—0.210	—0.221	±0.047
June	—0.129	—0.113	—0.066	—0.098	—0.112	—0.079	—0.144	—0.044	—0.059	±0.050
July	—0.202	—0.213	—0.223	—0.148	—0.155	—0.110	—0.238	—0.318	—0.338	±0.045
Aug.	—0.111	—0.207	—0.241	—0.364	—0.297	—0.207	—0.212	—0.224	—0.178	±0.044
Sept.	—0.295	—0.319	—0.283	—0.254	—0.201	—0.154	—0.169	—0.144	—0.226	±0.048
Oct.	—0.269	—0.276	—0.281	—0.255	—0.210	—0.247	—0.242	—0.296	—0.290	±0.047
Nov.	—0.034	—0.044	—0.176	—0.165	—0.068	+0.051	+0.038	0.000	—0.007	±0.050
Dec.	—0.130	—0.077	—0.127	—0.178	—0.183	—0.217	—0.159	—0.085	—0.095	±0.050
Year	—0.122	—0.121	—0.171	—0.228	—0.172	—0.132	—0.147	—0.161	—0.151	±0.014

TABLE 22, SECTION B

CORRELATION COEFFICIENTS BETWEEN DAILY BAROMETRIC PRESSURE AT KEW (DAY 0) AND BAROMETRIC GRADIENTS OVER NORTHERN PART OF NORTH ATLANTIC OCEAN (DAYS —3 TO 5), 1904-1909

	Day —3	*Day —2*	*Day —1*	*Day 0*	*Day 1*	*Day 2*	*Day 3*	*Day 4*	*Day 5*	*Probable error of highest coefficient*
Jan.	—0.099	—0.192	—0.326	—0.348	—0.250	—0.238	—0.162	—0.126	—0.065	±0.050
Feb.	+0.096	—0.062	—0.183	—0.160	—0.094	—0.099	—0.116	—0.091	—0.012	±0.053
Mar.	—0.026	—0.010	—0.096	—0.102	—0.041	—0.092	—0.071	—0.053	+0.015	±0.051
Apr.	—0.101	—0.037	—0.094	—0.175	—0.197	—0.199	—0.174	—0.153	—0.128	±0.050
May	—0.062	—0.102	—0.095	—0.125	—0.111	—0.047	—0.030	—0.005	+0.062	±0.050
June	—0.238	—0.214	—0.160	—0.149	—0.146	—0.155	—0.140	—0.087	—0.167	±0.048
July	—0.191	—0.166	—0.196	—0.140	—0.093	—0.132	—0.149	—0.158	—0.142	±0.050
Aug.	—0.056	—0.135	—0.272	—0.249	—0.225	—0.151	—0.131	—0.043	+0.015	±0.046
Sept.	—0.129	—0.145	—0.142	—0.132	—0.074	—0.019	—0.009	+0.006	—0.036	±0.050
Oct.	—0.160	—0.152	—0.229	—0.291	—0.214	—0.181	—0.169	—0.191	—0.194	±0.047
Nov.	—0.141	—0.264	—0.554	—0.560	—0.355	—0.210	—0.125	+0.004	+0.190	±0.036
Dec.	—0.302	—0.286	—0.274	—0.264	—0.203	—0.254	—0.158	—0.117	—0.056	±0.048
Year	—0.115	—0.151	—0.234	—0.242	—0.176	—0.160	—0.124	—0.093	—0.040	±0.014

TABLE 22, SECTION C

CORRELATION COEFFICIENTS BETWEEN DAILY ELECTRICAL POTENTIAL AT KEW (DAY 0) AND BAROMETRIC PRESSURE AT KEW (DAYS —2 TO 2), 1904-1909

	Day —2	*Day —1*	*Day 0*	*Day 1*	*Day 2*	*Probable error of highest coefficient*
Jan.	+0.028	+0.074	+0.295	+0.324	+0.178	±0.048
Feb.	—0.039	+0.040	+0.222	+0.236	+0.125	±0.049
Mar.	+0.181	+0.129	+0.398	+0.400	+0.248	±0.042
Apr.	+0.062	+0.061	+0.225	+0.172	+0.042	±0.048
May	+0.156	+0.184	+0.255	+0.277	+0.222	±0.047
June	+0.252	+0.291	+0.396	+0.326	+0.272	±0.042
July	+0.185	+0.221	+0.303	+0.253	+0.167	±0.047
Aug.	+0.150	+0.159	+0.328	+0.348	+0.147	±0.044
Sept.	+0.204	+0.218	+0.301	+0.291	+0.206	±0.047
Oct.	+0.197	+0.191	+0.295	+0.199	+0.145	±0.047
Nov.	+0.002	—0.001	+0.073	—0.031	—0.081	±0.052
Dec.	—0.037	—0.019	+0.122	+0.125	+0.037	±0.050
Year	+0.075	+0.093	+0.252	+0.235	+0.130	±0.014

cients between (a) sunspots and the electrical conditions at Kew (Table 20 and Fig. 33), and (b) sunspots and barometric gradients over the North Atlantic Ocean (Table 21 and Fig. 35), the barometric correlation lags two to four days after the electrical correlation. This suggests that if the relationship is one of cause and effect, the electrical conditions are a cause rather than an effect.

Another interesting point is the degree to which the maximum correlation between the daily electrical conditions at Kew and the barometric gradients over the Atlantic precedes or follows the corresponding correlation between the barometric pressure at Kew and the barometric gradients over the Atlantic Ocean. These correlations are given in Table 22. For the entire six years from 1904 to 1909 the correlation between the electrical conditions and the barometric gradients, both on the same day, Section A, is —0.228 (16.0 times the probable error), which means that high electrical potential at Kew is associated with gentle barometric gradients over the Atlantic. The correlation between the barometric pressure and the Atlantic gradients is —0.242, Section B. This indicates that high pressure at Kew is likewise correlated with gentle gradients over the Atlantic. For our present purpose the important point is that the barometric gradients over the Atlantic are correlated almost

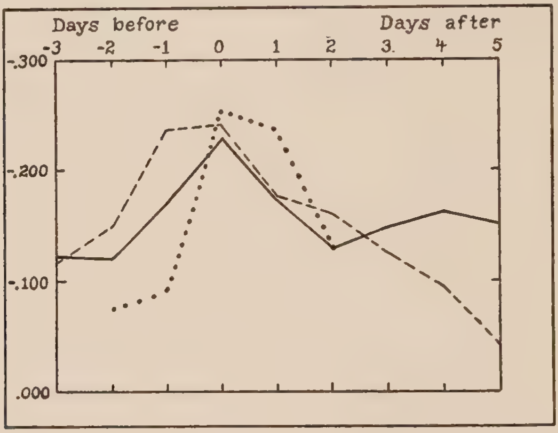

Fig. 38.

Correlation Coefficients, Electrical Potential Gradients at Kew, Barometric Pressure at Kew, and Barometric Gradients over North Atlantic Ocean, 1904-1909.

Solid line=electrical gradients at Kew and barometric gradients over North Atlantic.
Dash line=barometric pressure at Kew and barometric gradients over North Atlantic.
Dotted line—electrical gradients and barometric pressure at Kew.

equally with the electrical potential gradients and with the barometric pressure at Kew.

Let us now consider the relation of the barometric gradients over the Atlantic Ocean to the electrical and barometric conditions at Kew on days before and after the day when a given condition prevails at Kew. Since storms move eastward from the Atlantic Ocean to England, one would expect a given degree of barometric pressure at Kew to show an especially close correlation with the barometric gradients that prevailed over the Atlantic Ocean several days earlier. To put it in another way, suppose the barometric gradients over the Atlantic Ocean are unusually steep. That usually means that somewhere to the west of England a severe storm is raging. At London stormy conditions are also likely to prevail, or at least the barometer is likely to be low, presaging a storm, but the greatest period of storminess is not likely to occur until a day or two later. Hence we should expect the correlation between the pressure at Kew on any given day and the barometric gradients over the Atlantic a day or two earlier to be higher than the correlation between the pressure at Kew and the Atlantic gradients of the same day. This is not quite the case, as appears in Table 22 (Section B) and Fig. 38, for the highest correlation occurs when both phenomena are taken on the same day. Nevertheless, in six months out of twelve the correlation is highest when the pressure at Kew on a given day and the Atlantic gradients of a preceding day are compared, in five months the correlation is highest when the same day is used in both cases, while in only one month is the correlation highest when the pressure at Kew is compared with the Atlantic gradients of later days. In other words, as appears in the dash line of Fig. 38, although the synchronism between the Atlantic gradients and the pressure at

London is closer than might have been expected, the Atlantic gradients tend systematically to precede the correlated conditions of pressure at London.

A comparison of the electrical potential gradient at Kew with the barometric gradients over the Atlantic shows a somewhat different condition. The solid curve in Fig. 38 shows no tendency to be especially high on the day marked —1, or on any other day preceding the day of the observed electrical gradient. This means that there is no special correlation between the electrical potential at Kew and the barometric gradients of the preceding days over the Atlantic. On the other hand the solid line in Fig. 38 remains relatively high on the right while the dash line drops promptly toward zero. This suggests that the electrical gradients at Kew are correlated not only with Atlantic barometric gradients of the same day but of several days afterward. If the electrical conditions are primarily a result rather than a cause of the barometric conditions, we should expect that the lag would be the other way. That is, the electrical gradients at Kew would be correlated with the barometric gradients of preceding days more strongly than with those of following days. On the other hand, if the electrical conditions of the atmosphere are a cause of barometric conditions, we should expect them to show a higher correlation with the barometric gradients of succeeding than of preceding days. This latter condition is found, although only to a slight degree. Taking all parts of the solid and dash lines of Fig. 38 into account, they show that during the period from 1904 to 1909 high electrical gradients at Kew, gentle barometric gradients over the Atlantic Ocean, and high barometric pressure at Kew tended to occur on the same day, since both sets of correlation coefficients reach a maximum on the day designated 0. Nevertheless, there is a well-defined tendency for high electrical gradients to be followed by gentle barometric gradients over the Atlantic, and for these to be followed by high pressure at Kew. So far as these particular sets of correlation coefficients are concerned, an electrical condition precedes the conditions of atmospheric pressure with which it appears to be correlated.

Finally let us make a direct comparison between the daily electrical gradients and the barometric pressure at Kew. The correlation coefficients thus obtained are given in Table 22, Section C. In six months out of twelve the highest correlation is found when the electrical conditions are compared with the barometric pressure of the same day, and in five of the others when the electrical conditions are compared with the barometric pressure on the succeeding day. In only one case, November, does the correlation between the electrical potential and the barometric conditions of the preceding day (Day —1) rise nearly so high as the correlation with the succeeding day (Day 1). The way in which the barometric conditions lag after the electrical conditions is clearly evident in the dotted line of Fig. 38, representing the correlation coefficients for the year as a whole. Here, as in other cases, the electrical condition accompanies or precedes the correlated barometric condition, but does not follow it. This does not necessarily mean that the electrical conditions are the cause of the barometric conditions, for both may be due to some common cause which influences the electrical condition sooner than the barometric. It does mean, however, that the barometric conditions can scarcely be the cause of the electrical conditions as is often assumed. A common misapprehension is thus removed, and we are left free to consider why the order of events is (1) electrical conditions of the sun, (2) electrical conditions of the earth's atmosphere, and (3) barometric pressure. The natural assumption is that ordinary solar radiation and the heat into which it is converted offer the explanation. The only difficulty in this is that the type of solar energy with which we seem here to be dealing appears not only to be strongest on the sun's margins, but to have an opposite character on the opposite solar margins, no matter whether we pass from east to west or north to south.

As a result of this study of correlation coefficients between sunspots and barometric gradients, five important facts stand out clearly: First, from 1904 to 1909 the sunspots in the northern and southern hemispheres of the sun bore a different and opposite relationship to barometric gradients over the North Atlantic Ocean. Second, this relationship corresponded closely to the similar relationship between sunspots and atmospheric electricity at London, except that the signs of the coefficients were reversed. Third, the relation of the two solar hemispheres to the earth varied from season to season in such a way as to suggest that the solar hemisphere which is turned away from the earth has more effect upon barometric gradients than has the other. This relationship again is paralleled by that of atmospheric electricity, as shown in the monthly figures of Table 18. Fourth, there was such a lag from the electrical to the barometric phenomena of the earth's atmosphere that the barometric conditions can scarcely have been the cause of the preceding electrical conditions.

These are facts. The inference is that the electrical activity of the sun influences the electrical condition of the earth's atmosphere, and that this in turn has an effect upon the atmospheric pressure. Electrical emissions from the sun may not necessarily be the original cause of barometric highs and lows, but apparently they strengthen or weaken them, and perhaps change their paths or otherwise modify their life history. These facts and inferences are balanced against the seeming inadequacy of an electrical cause to produce the results expected from it. The matter cannot be decided positively as yet. To the author it seems that the weight of evidence is in favor of an electrical hypothesis. To persons of another temperament and training Humphreys' conclusion as to the quantitative inadequacy of an electrical hypothesis may seem more convincing.

Perhaps the case is like that of the sap ascending in trees. The ascent depends on gravitation, atmospheric pressure, capillary attraction, and osmotic pressure due to differences of chemical composition. But when these and all other known factors are combined, physicists have not been able to find any means by which the sap can be raised more than about 150 feet. Yet in spite of the quantitative inadequacy of our physical explanations, the sap in some trees does rise to heights of 200, 300, and even 400 feet. Some day we may discover physical reasons why sap rises so high and why barometric gradients show such close and complex relations to the atmospheric electricity and to the size and position of sunspots.

CHAPTER IX

METHODS OF TESTING AN ELECTRICAL HYPOTHESIS

IF there is really anything in an electrical hypothesis of atmospheric pressure, it ought to help in solving some of the perplexing problems of meteorology. An enumeration of a few of these may suggest lines of future investigation. For example, among the unexplained phenomena of weather, cyclonic storms hold an important place. In some respects their distribution is not wholly in accordance with what would be expected if they were due to contrasts in temperature. On the other hand, Kullmer[1] has shown that the average paths of cyclonic storms in both the northern and southern hemispheres are roughly concentric with the magnetic rather than the geographical poles. If land and sea with their contrasts of temperature and atmospheric pressure did not disturb the storms, the main tracks would apparently be nearly parallel with the magnetic equator. Bigelow and Bumstead have both suggested an electrical explanation of this, but no one has done any quantitative work to see whether the explanation is adequate. The gist of the suggestion is that on their way from the sun to the earth the electrons must be deflected from a straight course by the magnetic field not only of the sun, but of the earth. If there were no deflection by the earth's magnetic field, the distribution of the electrons would be like that of light. In other words, their total number per unit area at any given season would decline from the zone where they fell vertically to the places where they fell tangentially. Since the electrons must be magnetically deflected, however, they may be concentrated in certain zones which would tend to be roughly concentric with the magnetic poles. In these belts, variations of pressure, no matter from what cause they arise, may possibly be electrically intensified.

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[1] C. J. Kullmer: in The Solar Hypothesis of Climatic Changes, Bull. Geol. Soc. Am., Vol. 25, 1914.

This leads to another suggestion as to an interesting line of possible investigation. If solar electrons are magnetically deflected, any appreciable alteration in the strength of the earth's magnetic field may be reflected in some alteration in the location of storm tracks. We have already quoted Bauer's conclusion that at times of many sunspots the activity of the sun tends to weaken the earth's magnetic field. We have also seen that Kullmer's study of storm tracks suggests a northward shifting of the main storm track in the United States at times of many sunspots. Moreover, Clayton also finds a latitudinal shifting of the sun's zones of greatest influence during each sunspot cycle.

These facts raise the question whether a weakening of the magnetic field—if it were able to produce any effect whatever, which is doubtful—would tend to give the storm tracks a more equatorial or a more polar position. At first thought it seems as if a weakened field would cause less deflection of the solar electrons and shift the storms into lower latitudes. On the other hand, certain experiments of Birkeland[2] suggest the opposite possibility, although it is not at all certain that the experiments really have any relation to the present problems.

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[2] Kr. Birkeland: The Origin of Worlds, Sci. Am. Supplement, Vol. 76, 1913.

Birkeland's method was to place a small steel globe in a large vessel from which the air had been exhausted, and subject it to electrical discharges ranging up to 400 milliamperes in intensity. The larger the globe, the more noteworthy the results. The main result was a series of small bright spots on the surface of the globe. These were due to disruptive electric discharges from the globe itself, which succeeded one another rapidly and sometimes actually carried off bits of steel. When the globe was not magnetized, the spots were distributed irregularly, but when it was magnetized, even feebly, the spots arranged themselves in two zones parallel to the magnetic equator of the globe. The more strongly the globe was magnetized the more closely the spots approached the equator. Moreover, many of the spots showed numerous arms projecting in all directions and curved so that they appeared to indicate vortices. They revolved in opposite directions on the two sides of the magnetic equator. In this respect, and in their zonal distribution parallel to the magnetic equator, and also in their tendency to locate themselves in high latitudes with a weak degree of magnetization and move toward lower latitudes as the strength of the magnetic field increased, there seemed to Birkeland to be an analogy between the little spots on the steel globe and sunspots.

In all these respects Birkeland's spots seem also to present some analogy to terrestrial cyclonic storms. This raises the question whether on a magnetized globe as huge as the earth an electrical charge derived from the sun could cause discharges from the outer air which would set up vortices and help to give rise to storms. The answer to this question offers a most interesting field of investigation. Meanwhile all we can say is that if Birkeland's spots behave in the same way as cyclonic storms, and if changes in the earth's magnetic field are competent to produce any effect upon storms—both of which are doubtful—a weakening of the earth's magnetic field, such as occurs at times of sunspot maxima, would cause the cyclonic storms to follow courses relatively far from the magnetic equator, which accords with the facts as reported by Clayton and Kullmer.

Another field where an electrical hypothesis may be a help to investigators is suggested by the conclusion of Helland-Hansen and Nansen[3] that many lines of evidence seem to demand some supplement to the ordinary thermal hypothesis. These Norwegian authorities amplify the work of Hildebrandssohn and others in showing that the centers of atmospheric action, as we have already seen, are of two great types which agree roughly with areas of high and low pressure. In these two types the changes in pressure occur simultaneously, but in opposite directions. Variations in temperature also take place simultaneously in opposite directions. Again, the curves of temperature or pressure in widely separated areas often run closely parallel for a series of years, and then suddenly change so that they are directly opposite to one another. The resemblance and the opposition are so marked that a relationship seems almost certain. Moreover, several such reversals are evident when some of the long periods are compared. Even if all these phenomena can be explained on a purely thermal hypothesis, they seem to Helland-Hansen and Nansen to emphasize the importance of the effect of solar variations upon the upper layers of the air. Most authors, they say, have not given proper weight to the fact that a great part of the solar radiation is absorbed in the higher layers of the atmosphere. According to their figures, 40 per cent is lost by reflection; another 40 per cent is lost by absorption in the upper air, and only 20 per cent reaches the earth's surface. They hold that the 40 per cent absorbed in the upper air plays

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[3] Helland-Hansen and F. Nansen: *op. cit.*

> perhaps the greatest part in determining the temperature of the surface of the earth. . . . This distribution of temperature in the atmosphere is in a high degree dependent upon the circulation of the atmosphere itself. This again is dependent upon the thermal emission of the radiation of the sun and perhaps also on other forms of energy radiation.

They do not agree with Newcomb, who, misled by the paradox of a hot sun and a cool earth, held that ''magnetic radiation'' is too small to have any direct influence on meteorological phenomena. As the two Norwegians put it, Newcomb

> thinks that on this account the magnetic, electrical, and radioactive radiation of the sun can be completely left out of account. He seems here to forget that the variations in the solar activity and in the solar constant, and also in the electrical radiation of the sun, are primarily affecting the higher layers of the air and thereby the atmospheric circulation not only in these higher layers, but also in the lower part of the atmosphere.

The preceding quotations reflect a tendency which is becoming more and more common among students of meteorology. It is a tendency to ascribe a growing importance to changes in the upper air arising from variations in solar energy, regardless of whether the energy takes the form of light or electrical emissions. Such an attitude proves nothing as to the specific electrical hypothesis now before us, but it may indicate that some of our meteorological conceptions need revision. It should be especially noted that one of the main reasons why Helland-Hansen and Nansen feel the need of such revision is the fact that the old explanations do not seem to them to explain fully how simultaneous changes of both temperature and pressure in opposite directions can occur in regions differing by no more than ten or twenty degrees of either latitude or longitude. On the other hand, the electrical hypothesis, by its very nature, may require opposite results in areas of high pressure and low pressure.

In this connection something should be said about another kind of reversal which may in the future throw light on the method by which the sun influences the weather. At the Mount Wilson Observatory, as has already been noted, Hale and his associates[4] found that near the sunspot minimum in 1912 the polarity in the more deeply lying parts of the spots was reversed. Where positive spots had been the leaders in the bipolar pairs, negative spots took their place; and the arrangement of the bipolar pairs in the southern hemisphere became as it had previously been in the northern, and vice versa. We have already suggested that the Lockyers may have observed a similar reversal about 1896 without realizing just what it was. It may be worth while for someone to investigate the possibility that the solar reversals may have been the cause of certain reversals in the apparent relations between the earth and the sun, and between one part of the earth's lower atmosphere and another.

It has not yet been feasible to investigate similar reversals since 1912, partly because the Great War delayed the publication of records and partly because of the great amount of labor involved. The delayed effect of this sudden change of sign may possibly be seen in the contrast between the remarkable deficiency of storms in the northern United States and southern Canada in 1911,

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[4] Reported in Monthly Notices, Roy. Astron. Soc., Vol. 80, 1920, p. 412.

1912, and 1913, as illustrated in Figs. 15 to 17, and the sudden great excess in 1914, as shown in Figs. 18 and 19. If the earth's magnetic field is closely dependent upon the sun, as Bauer believes, a change of polarity in the sunspots might possibly upset the magnetic equilibrium which had been more or less established on the earth during the preceding conditions of polarity, and weaken the earth's magnetic field. If the earth's magnetic field has anything to do with cyclonic storms, such a weakening might tend to drive the storms away from the earth's magnetic equator, provided they act like Birkeland's spots. If the disturbances of the sun's atmosphere increased at the same time, as they appear to have begun to do in 1914, we might perhaps get the contrast which makes Fig. 17 show an excess of storms in the central parts of the United States in 1913, while Fig. 19 shows an excess farther north in 1914. The fact that the change in solar polarity occurred, or at least began, in 1912, while the change in storms did not become fully effective till 1914 must not be overlooked. It may mean that there is no such relationship as is here suggested, or it may mean merely that it takes time for so radical a solar change to become fully effective in the sun itself and then in the earth's atmosphere. This, however, does not affect our present discussion. We are here merely indicating certain phenomena connected with storms which need investigation with both the thermal and electrical hypotheses in mind. Of course such a piling up of "ifs" as we have had in this paragraph means that there is a long road to be traveled before any definite conclusions can be reached. But such suppositions are a necessary prelude to many important discoveries.

The paradox of a hot sun and a cool earth is another phenomenon which should be studied in this connection.

It will be remembered that when sunspots are numerous and the solar constant is high, the earth's surface, on an average, is relatively cool. Two explanations of this are discussed in an earlier chapter, namely, Humphreys' hypothesis of the effect of ultra-violet light on ozone in the upper air, and the hypothesis of cyclonic storms. It seems almost certain that the sun's electrical emissions are stronger at times of many sunspots than at times of few. If such emissions really cause an increase in cyclonic storms, they may help to explain the cooling of the earth. The solar constant is indeed higher than usual, and to that extent tends to make the earth unusually warm. But if storms are initiated or intensified by the sun's electrical activity, they may act in an opposite way and lower the temperature at the earth's surface. Of course this is no proof of an electrical hypothesis but merely another case where the peculiar solar and terrestrial relations described in previous chapters suggest that further investigation may be profitable.

Another case of the same kind is found in semidiurnal variations of barometric pressure.

> It has been known now for two and a half centuries that there are more or less regular daily variations in the height of the barometer, culminating in two maxima and two minima during the course of 24 hours. . . . Probably the earliest observations of these rythmical daily changes . . . were made by Doctor Beal during the years 1664-1665, and therefore very soon after the invention, 1643, of the mercurial barometer. Since Beal's discovery the same observation has been made and puzzled over at every station at which pressure records were kept and studied, but without success in finding for it any adequate physical explanation.[5]

The usual explanation of the semidiurnal variations of atmospheric pressure is as follows. The drop during the middle of the day (Fig. 39) and the minimum about 4 p.m., which are characteristic of many parts of the earth at low levels and over the lands, are reasonably and convincingly explained as due to the heating of the air by the sun and its consequent expansion and overflow at high levels. The rise in pressure during the first part of the morning is less satisfactorily explained on the supposition that when the air close to the earth's surface first becomes warm, the restraint of friction does not permit it immediately to be replaced by cooler air from above. Hence there is a temporary rise of pressure due to the expansion of the lower air and its attempt to crowd upward. For the rise of pressure in the late afternoon and evening, with a maximum about 10 p.m., and for the minimum at about 4 a.m., it has been suggested that when the air is once set in rhythmic motion by the rise of pressure in the morning and the fall in the afternoon, it continues to vibrate with the same periodicity. The maximum and minimum during the night are supposed to be free vibrations, that is, vibrations which have no immediate cause, but are waves, so to speak, set in motion by the forced vibrations of the daytime. This hypothesis can scarcely be said to have an observational basis. It is based on calculations which suggest that the mass and volume of the air are such that an atmospheric wave when once started will have a period of approximately twelve hours. There is, of course, no inherent impossibility in this, but on the other hand there is no evidence of it aside from the barometric variations for which it is advanced as an explanation.

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[5] W. J. Humphreys: Physics of the Air, 1920, pp. 229 and 231.

On the other hand, Chree's[6] study of diurnal variations suggests an electrical cause. Atmospheric electricity and barometric pressure are the only elements of the weather that show a double daily oscillation. Temperature, sunshine, cloudiness, rainfall, wind, and convection all display a single maximum and a single minimum. Other electromagnetic elements, however, such as the earth currents discussed by Bauer[7] at Ebro and Berlin, show a double maximum like that of atmospheric electricity. The relation between atmospheric electrical potential and barometric pressure at Kew, as worked out by Chree, is illustrated in Fig. 39. In a careful analysis of the conditions at London, he shows that both curves of Fig. 39 appear to be composed of two distinct parts. One of these, the less obvious, consists of a curve with a single maxi-

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[6] C. Chree: A discussion of atmospheric potential results at Kew from selected days during the seven years 1898 to 1904, Phil. Trans. Roy. Soc., Lon., Vol. 206 A, 1906, pp. 299-334.

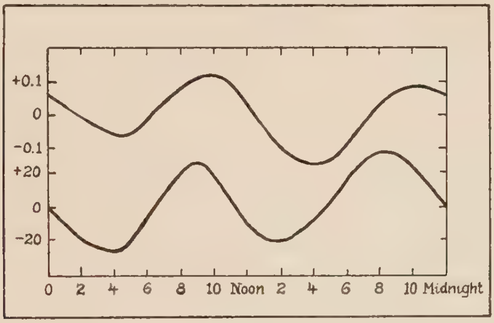

Fig. 39.

Diurnal Variations in Barometric Pressure (upper) and Atmospheric Electrical Potential Gradients (lower) at Kew.

(*After Chree.*)

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[7] L. A. Bauer: Some Results of Recent Earth-Current Observations and Relations with Solar Activity, Terrestrial Magnetism, and Atmospheric Electricity; Terrestrial Magnetism and Atmospheric Electricity, Vol. XXVII, 1922, pp. 1-30.

mum and minimum during the twenty-four hours; the other is the obvious curve with two maxima and two minima. The two curves with a single maximum and minimum are directly opposite in character, the pressure curve being highest at night or early in the morning when the electrical curve is lowest. The pressure curve acts as would be expected if it were due to the difference in temperature between day and night, as is almost certainly the case. The electrical curve, on the contrary, acts as would be expected if the electrical potential tended to become high under the influence of the sun.

As to how the two curves are related, we may best quote Chree (p. 331):

> Whilst the resemblance is very striking, as between two different elements, there are differences which seem of a fundamental character. During the forenoon the curves are nearly in the same phase. The barometer curve lags a little, but very little, behind the other. In the afternoon, however, the lag in the barometer curve becomes conspicuous, amounting to about two hours at the times of the afternoon maximum and minimum. This change in apparent lag throughout the day does not seem to have been noticed previously, but it persists with wonderful regularity throughout the year. . . . If the relation is a case of cause and effect, the fact that it is the barometric curve that lags relative to the other would naturally lead one to regard the potential variation rather as the cause than the effect.

Since Chree's paper was published, Mauchly's work has introduced a new element into the problem. He found, it will be remembered, that the potential gradient in the air over the oceans shows a maximum at the same hour in widely separated regions. This does not mean the same hour of the day, but absolutely the same hour by Greenwich time, as explained in Chapter VI. If atmospheric electricity really has an effect upon barometric pressure, this discovery must be reckoned with. A combination of Mauchly's curve with the curve showing the variations of electrical potential due to the local effects of the earth's rotation may help to explain the semidiurnal variations of atmospheric pressure. Investigation of this whole question is another of the many interesting problems for which the necessary observations are rapidly accumulating.

It must not be supposed that these suggestions as to the investigation of solar and terrestrial electricity imply that there is the slightest possibility of displacing the view that ordinary solar radiation is the main determinant of the earth's climate and weather. No one can watch the march of the seasons or compare the climate of different parts of the earth without seeing that the sun's heat is far the most important element in determining the conditions of both climate and weather. What we are here emphasizing is merely the fact that certain phenomena, perhaps minor phenomena, do not seem to conform to a strict thermal hypothesis and that therefore some other hypothesis may be necessary. An electrical hypothesis seems to explain these facts, but is independently indicated by a study of the sun. Inasmuch as an electrical hypothesis seems to be suggested by our study of sunspots and weather, it would seem advisable to investigate it fully.

In order that there may be no misapprehension as to our view of the importance of solar heat, and also in order that we may clearly visualize the probable contrast between thermal and electrical effects, it seems advisable to consider briefly certain facts as to the meteorological effect of variations in the solar constant. For a far fuller and more authoritative statement the reader is referred to H. H. Clayton's *World Weather.* In fact, that book and this might well be read together as presenting two wholly different but, in most respects, harmonious views of the solar phases of meteorology.

The solar constant is subject to innumerable variations. It varies from hour to hour, from day to day, and from year to year. In general its main variations are in harmony with those of sunspots, although sometimes, especially when spots are scarce, their area and the solar constant seem to have little or no connection. In this respect the solar constant and solar electricity act alike, and probably they are intimately related. Theoretically the first effect of an increase of the solar constant would be to heat all parts of the earth's surface; but regions where the pressure is high would be more heated than those in the same latitude where it is low. This is because the air in high pressure areas is relatively clear and dry. Hence the sun's radiation can pass through it and reach the earth with less loss than in damp, cloudy areas of low pressure. There, on the contrary, absorption by atmospheric vapor and especially reflection from clouds prevent a considerable part of the solar radiation from reaching the earth. Thus, while all parts of the lower air might be warmed somewhat by a rise in the solar constant, the land in clear high pressure areas would be warmed by day more than lands of similar character in cloudy low pressure areas. Hence the air in such highs would expand more than in the lows. This might cause a slight compression and a short-lived increase in pressure, although nothing of the kind appears to have been demonstrated. The main effect would be that some air would flow from high pressure to low pressure areas at high altitudes. Thus the barometric gradients would be diminished, for the pressure in the highs would be lowered, while in the lows it would be raised.

Suppose now that we look beyond the first day and ask what would happen when abundant solar radiation has had time to complete its work. The effect would ultimately be to increase the contrasts of temperature from zone to zone. Since the amount of solar energy falling on a given area of the earth's surface varies according to latitude, the extra amount due to increased radiation must vary in the same proportions. Thus with a high solar constant equatorial latitudes must be warmed more than others. Consequently the zones of pressure must be intensified, and the barometric gradients strengthened. Because of the great distances from the center of one zone of pressure to that of the next, the steepening of the zonal gradients would not occur so quickly as would the flattening of the gradients between neighboring highs and lows in the same latitude. Hence we should expect that the main effect of a rise in the solar constant would be first a decrease in barometric gradients, followed later by a rise.

This is what actually happens, as may be seen in the upper part of Fig. 40.[8] There the solid line shows what happens to the gradients on and after days of high solar constants, and the dotted line after days of low constants. On the first day after high constants the low position of the solid line means that the barometric gradients in the Atlantic Ocean flatten out, just as would be expected.

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[8] The method employed in preparing Fig. 40 is almost the same as in Figs. 5 and 6, where sunspots are compared with the gradients over the North Atlantic Ocean, but differs a little because the figures for the solar constant are not available for every day nor for the whole year. For the years 1906, 1908, and 1909, all the days for which Abbot gives the solar constant have been used, and have been divided into three approximately equal groups for each year on the basis of the solar constant. The groups with the highest and lowest constants, respectively, were used as the basis for tabulating the subsequent departures of the barometric gradients from the normal in both sections of the North Atlantic. The smoothed results appear in Fig. 40. Data for the solar constant are available only from May or June to October or November.

For the next seven days, however, they rise, until on the eighth day they are distinctly above the normal. In the same way, on the first day after low solar constants the barometric gradients are stronger than usual, as appears in the dotted line, for the contrast between highs and lows is increased by the more rapid fall in the temperature of the clear, dry highs. Later, however, just as would be expected, the gradients decline, and after nine or ten days reach a low level because the contrasts between the zones have diminished. It seems, then, to be fairly well established that the immediate accompaniment of a high solar constant is reduced gradients, while that of low constants is high gradients, at least in the North Atlantic region. Later, however, the effect is reversed when the zones become fully adjusted to the new solar condition, and the maximum effect of increased solar radiation is seen in high gradients after about a week.

This conclusion is reinforced by the work of Clayton.[9] He finds that at Buenos Aires high solar constants are accompanied by relatively low temperature, but are followed by a steady rise until the tenth day, as appears in the solid line in the lower part of Fig. 40. On the other hand, low solar constants are accompanied by temperatures above the normal, but are followed by low temperature from four to ten days later, as appears in the lower dotted line. A comparison of the upper and lower parts of Fig. 40 discloses a noteworthy agreement between the fluctuations in temperature at Buenos Aires on the one hand and in barometric gradients over the North Atlantic Ocean on the other, when both are compared with variations in the solar constant. In another part of the world, Helland-Hansen and Nansen find that "there is a very well-developed positive correlation between the solar radiation and the pressure gradients between Christiania and Bergen,'' the correlation coefficient rising to +0.63 on the fifth day after any given condition of solar radiation. Thus it appears that normally a high solar constant is at first associated with a flattening of the barometric gradients, followed during five or ten days by a somewhat steady increase both in the temperature at the earth's

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[9] H. H. Clayton: Variation in Solar Radiation and the Weather, Smiths. Misc. Coll., Vol. 71, No. 3, 1920.

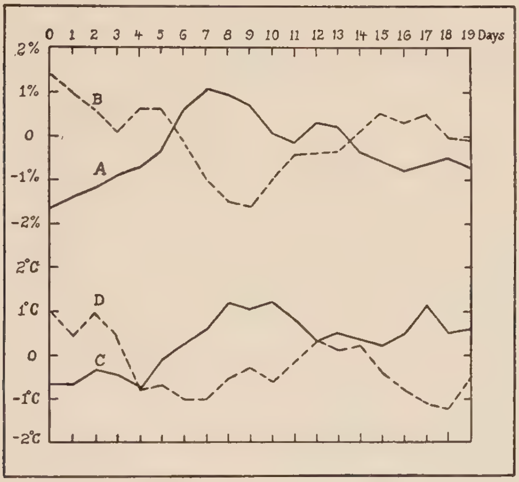

Fig. 40.

Relation of the Solar Constant to Barometric Gradients and Temperature.

Upper curve=departures of barometric gradients from normal over North Atlantic Ocean, after days having (A) high solar constants (solid line) and (B) low solar constants (dotted line). All the available days in 1906, 1908, and 1909 were divided into three groups on the basis of the solar constant, and the two extreme groups were here used.
Lower curves=departures of temperature from normal at Buenos Aires after days having (C) solar constants above 1.97 (solid line) and (D) solar constants below 1.93.

surface and in barometric gradients. This accords with the idea of Helland-Hansen and Nansen that heat absorbed in the upper layers of the atmosphere may be the most important factor in determining the earth's purely thermal relations. If they are right, the effect of a high solar constant would not become manifest on the earth's surface until after the lapse of sufficient time for a considerable body of the upper air to be brought down to low levels by convection.

Much other evidence might be presented to show that variations in the solar constant are associated with variations in the weather. The great difficulty is to disentangle the thermal effects from the smaller and less conspicuous electrical effects. The sun's thermal radiation and its electrical condition vary closely together. Suppose that an electrical disturbance alters the earth's barometric gradients when it first appears on the sun's eastern margin and thereby leads to variations of temperature. As the disturbed solar area approaches the sun's central meridian the electrical effect may die out, but radiation may increase. Under such conditions it is very difficult to determine whether a certain effect is a delayed consequence of electrical emissions or an immediate response to radiation. When the electrified part of the sun's disk reaches the western margin and is about to disappear, the difficulty of distinguishing between its immediate electrical effect and the delayed effect of radiation when the disturbed area was near the sun's center may be even greater.

Bearing in mind this difficulty, and recognizing that the effects of solar radiation and of solar electricity are almost inextricably intermingled, we may tentatively set down the following points in which the two types of solar energy seem to differ:

(1) Changes in the ordinary radiation of the sun require several days (four to ten in the examples here given) to produce their full effect; electrical changes seem to produce their full effect more quickly, probably within two to four days of the time when they occur.

(2) Solar radiation must act primarily through temperature. It must also at any particular moment act in the same way in all parts of the world, even though the extent to which the temperature is altered may vary greatly and the effects may speedily be masked by secondary effects due to convection, clouds, rain, winds, and currents. The sun's electrical changes, on the contrary, appear to have no direct effect upon temperature. They work through barometric pressure. Moreover, a given solar change not only may, but apparently must, differ in its effect on the air according to whether the most effective spots are positive or negative, and also, perhaps, according to whether they act upon areas of high or low pressure. Secondarily, the changes in barometric pressure arising from electrical changes may alter the temperature, and are thus likely to be confused with the effects of radiation.

(3) From the thermal point of view the central parts of the sun's disk are usually supposed to be primarily important; the marginal portions, because of their inclination away from the earth, are assumed to be relatively ineffective. From the electrical point of view the marginal areas are most important, presumably because the sun's magnetic field alters the paths of the charged particles emitted from areas of disturbance.

It should be noted, however, that Clayton[10] has advanced the hypothesis that solar prominences or other forms of ejected matter cause the sun's margins to be thermally more important than the central parts of the disk. The argument is that when hot gases are ejected from the lower layers of the sun, they do not increase the radiation from the central portions. In fact, the cooling of the gases as they are projected, perhaps hundreds of thousands of miles beyond the sun's so-called surface, may cause them to act as a screen and prevent the escape of a certain amount of radiation from the lower and hotter solar layers. On the other hand, when similar prominences are ejected from the marginal parts of the solar disk, they send their radiation to the earth along lines tangential to the sun. They do not shut out any radiation from the sun itself, but on the contrary they actually increase the area whence radiation proceeds earthward. Thus it is possible that while the main thermal effect of the sun depends on the central areas, the margins may cause more *changes* in the amount of radiation than do the centers. From this point of view electrical and thermal radiation may be similar, but this does not explain or alter the next of the differences between the sun's ordinary radiation and its electrical emissions.

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[10] H. H. Clayton: World Weather, New York, 1923, p. 290. Also Nature, Vol. 107, March, 1921, p. 108.

(4) The most important difference between ordinary radiation and electrical emissions from the sun is the fact that ordinary radiation produces the same effect whether it comes from the sun's eastern or western margins, or from the northern or southern solar hemispheres. The effect of electrical emissions from the sun's eastern margin is apparently the opposite of the effect of emissions from the western margin. Sunspots in the northern and southern hemispheres likewise appear to act in opposite ways. This difference between ordinary solar radiation and electrical emissions is so peculiar, so pronounced,

and so closely in accord with the bipolarity of sunspots that it is difficult to explain unless there is an electrical as well as a thermal control of the earth's atmosphere by the sun.

CHAPTER X

THE ORIGIN OF SUNSPOTS

THUS far in this book we have been seeking to discover the direct causes of changes in the weather. We have been led to conclude that solar disturbances rank among the most important of such causes, and that the disturbances may act electrically as well as thermally. If our investigation is to proceed as far as possible toward ultimate causes, one of the next steps is to investigate the reasons why the sun is disturbed. Hence this chapter is devoted to the astronomical or astrophysical problem of the origin of sunspots.

It is generally agreed that sunspots are merely the most noticeable portion of a series of connected phenomena which include (1) the general solar radiation, which is expressed in terms of the solar constant, (2) sunspots, (3) faculæ, flocculi, prominences, and coronal activity, (4) electrical and magnetic disturbances, and (5) horizontal movements corresponding perhaps to winds. Each of these probably has its counterpart on the earth, where all the corresponding phenomena appear to vary more or less closely in harmony with variations in atmospheric pressure and storminess.

(1) The general radiation of the sun in the form of light owes its variations to the combined effect of all the activities which seem to keep the sun's atmosphere in a constant state of turmoil. The welling up of hot vapors, the ejection of streams of hot gas in prominences and the

downward movement and veiling effect of the gases that have been shot out all play a part.

(2) Sunspots appear to correspond to cyclonic areas on the earth. At any rate the ordinary spot seems to consist of a funnel of ascending gas, the relatively dark center of which contains a column of descending gas suggesting the column of descending air which forms the eye of a tropical hurricane. The dark umbra and the less dark penumbra which form the most noticeable part of a sunspot are supposed to appear dark merely because their ascent has allowed them to expand and become cool so that they are not quite as hot as the masses of vapor around them. In the atmospheres of both the earth and the sun masses of relatively warm gas presumably rise in cyclonic areas, move out from such areas at high levels, and ultimately sink in anticyclonic areas. The only actual descent of gas that appears to have been measured, however, is in the centers of sunspots, a type of motion which has been found by Hale and his associates.[1] In the hydrogen vortices at high levels above sunspots the solar atmosphere moves spirally inward and downward with probably an outward flow in the lower chromosphere. Below the chromosphere, ''in the spots themselves,'' the movement is ''spirally upward and outward along the sun's surface.''[2]

(3) The faculæ, flocculi, prominences, and coronal masses appear to be hot clouds of vapor. They may be analogous to the warm air carried aloft in cyclonic storms upon the earth, but many authorities think that they owe their high temperature to the compression incident to their fall back into the sun after having been shot to high levels.

[1] G. E. Hale: Astrophysical Jour., Vol. 49, p. 183.

[2] Monthly Notices, Roy. Astron. Soc., Vol. 80, 1920, p. 412.

(4) The electrical phenomena of the solar atmosphere appear to correspond to those on the earth. That is, they become intensified when the cyclonic circulation increases and diminish when it falls off. Magnetic conditions also appear to be altered in the same way, for they apparently depend on local electric currents in the solar atmosphere. In this connection the peculiar reversal of the electrical signs of sunspot pairs at the time of the sunspot minimum in 1912 should again be noted. The nature of sunspots, and especially their electrical relations, are evidently very complex.

(5) The fact that the sun's atmosphere apparently contains cyclones probably means that there are also anticyclones and presumably movements from high pressure to low, corresponding to the winds on the earth's surface and compensating for the movements in the other direction at higher levels. Evershed and St. John have indeed found evidence of what might be called winds, for near the bottom of the visible portion of sunspots the gases move radially outward, presumably at the top of the sunspot vortex, while about 2500 miles higher there is no motion and at levels of 10,000 to 15,000 miles the motion is inward toward the centers of the spots.[3] These movements perhaps correspond to those near the eye of a tropical hurricane, rather than to the transfer of gases between cyclonic and anticyclonic areas. Bigelow,[4] in his two books on the sun and the earth, lays great stress on the unity of the laws governing the two atmospheres.

Granting a general resemblance between certain phases of the circulation in the outer parts of the sun's atmosphere and that of the earth, let us inquire how the solar circulation probably arises. Since the sun receives no appreciable amount of heat from outside sources, it is commonly assumed that its atmospheric circulation is convective in nature and arises from loss of heat and contraction. The localization of sunspots and of other evidences of special activity is frequently and perhaps commonly assumed to be due to differences in the composition of the solar atmosphere not only vertically but horizontally, or else to the differing rates of rotation in different latitudes. Without attempting to pass upon the truth of these assumptions, let us consider certain facts which seem to suggest that some other cause is also needed in order to explain the location and periodicity of the spots. These facts pertain first to the chemical composition of the solar atmosphere; second, to the latitudinal arrangement of sunspots; third, to their periodicity; fourth, to their regular appearance in certain latitudes, followed by a gradual change of the sunspot zone to lower latitudes as each cycle progresses, and, fifth, to their contrast with another and apparently truly convectional type of circulation in the solar atmosphere.

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[3] Chas. E. St. John: Radial Motion in Sunspots, Astrophysical Jour., 1913, Vol. 37, 322 ff.; and Vol. 38, 341 ff. Also contributions from Mt. Wilson Solar Observatory, Nos. 69 and 74.

[4] F. H. Bigelow: The Sun's Radiation and Other Solar Phenomena; A Meteorological Treatise on the Circulation and Radiation in the Atmospheres of the Earth and Sun, New York, 1915.

(1) The violence of sunspots and of the related phenomena seems to be so great that in a gaseous atmosphere like that of the sun differences in chemical composition from latitude to latitude ought to have been eliminated long ago, as has happened in the atmosphere of the earth. Or if they arise through the upwelling of gases from lower regions, it would seem as if they ought to be distributed quickly throughout the entire atmosphere, as happens with the volcanic dust and other impurities which are thrown into the earth's atmosphere. In the so-called prominences jets of gas are often thrown out to a

distance equal to that of the moon from the earth; their velocity sometimes reaches 50 miles a second. Relatively speaking, this is much as if the materials of a volcanic eruption should rise to a height of 2500 miles from the surface of the earth. With disturbances of such magnitude it does not seem probable that local differences in the composition of the sun's outer portions can persist for any great length of time.

In spite of the constant mixing of the gases composing the solar atmosphere, a mixing which has presumably gone on for thousands of millions of years, sunspots are preëminently a phenomenon which is localized in two well-defined belts in low solar latitudes. Very few occur more than 35° from the equator, and the vast majority are in latitudes 10° to 30° on either side of the equator. In the intermediate equatorial belt they are rare. We are so accustomed to an earth which is heated more at the equator than anywhere else that it seems perfectly normal to find the sun's atmosphere especially disturbed in belts arranged symmetrically on the two sides of the equator. As a matter of fact, however, this is a highly specialized arrangement. If the movements of the sun's atmosphere were due to internal differences of structure or chemical composition, and to consequent differences in the rate of cooling or in the ejection of matter from the interior, it is scarcely credible that the spots should be thus distributed. On the contrary, it would seem that the places where cooling takes place with special rapidity or with special slowness ought to be distributed irregularly according to the law of chance and ought to occur in high latitudes and at the equator as well as in the two belts.

(2) The fact that the surface of the sun rotates at different speeds in different latitudes may be suggested as

a reason for the zonal arrangements of the spots. At the equator the rate of rotation, as viewed from a fixed star, is about 25 days, in latitude 20° it is 26 days, and so on up to about 32 days in latitude 75°. As seen from the revolving earth the rotation is from a day and a half to two days longer than the periods stated above. In the sunspot zone the average is about 27.2 days. The diminution in speed per degree of latitude is greater in the zones on the poleward side of the sunspots than in the sunspot zones. This would seem to demand more sunspots in high latitudes than in low, a condition quite contrary to that which actually prevails. If the sunspots be ascribed to the cause now commonly assigned for cyclones on the earth, the case is no better. According to what seems now to be the prevailing view, terrestrial cyclones are due to polar cooling and the resulting equatorward flow of cool, heavy air. But barring whatever effect may be produced by the sunspots themselves and the related phenomena which we are trying to explain, there is little reason to think that the rate of cooling is any faster in one solar latitude than in another. From this point of view the pronounced zonal arrangement of sunspots seems to be at variance with an internal cause, but may be in harmony with an outside cause.

(3) The periodicity of sunspots seems equally out of harmony with an internal cause. Birkeland,[5] to be sure, has supposed that the spots are due to some sort of volcanic effect which has a periodicity like that of geysers. This, however, assumes that the sun is solid and that the sunspots are volcanic in nature,—an idea which has received little support since Birkeland wrote his paper. No

[5] Kr. Birkeland: Recherches sur les taches du Soleil et leur origine, Skrift. Videnskab., I, Christiania, 1899, pp. 1-173.

other explanation of the eleven-year cycle on the basis of the sun's internal activity seems to have been suggested.

(4) Again, the fact that sunspot cycles begin with spots in relatively high latitudes, about 35°, and that spots gradually appear in lower latitudes as the cycle advances, seems more in harmony with external than internal causes. If we appeal to an internal cause, it must be something which lies all around the sun at about the same latitude on each side of the equator, and which becomes active in all longitudes and in both hemispheres at essentially the same time. An arrangement of that sort may be possible, but it is scarcely probable, and there is no evidence that it exists. Thus if sunspots are of internal origin we are confronted by four highly perplexing conditions which do not seem consonant with such an origin: (a) the violent mixing of the atmosphere in the spots themselves and hence the tendency to give the solar atmosphere a uniform composition; (b) the occurrence of spots only in certain well-defined and limited belts which obviously have some relation to the equator; (c) the definite although variable periodicity of the spots; and (d) the fact that the sunspot cycles regularly start in a definite latitude. On the basis of an external cause all these conditions are not only reasonable but expectable.

(5) In addition to the preceding negative arguments there is a positive argument as to the type of convective circulation to be expected on the sun. The sun has two kinds of atmospheric movements: (A) Sunspots and the related phenomena of faculæ, prominences, and so forth, and (B) the rice grain structure or pores. The rice grains are small bright spots dotted over the sun's surface and separated by slightly darker areas. They suggest the bits of cloud seen in a mackerel sky. While there is still dispute as to their exact nature, it is generally agreed that

they represent the sun's convectional circulation arising from loss of heat. The outer layers of the sun's atmosphere undoubtedly cool rapidly. They thus presumably become heavy and sink, thereby causing some kind of circulation. Such a circulation probably would assume a somewhat cyclonic character, much as the dustwhirls over deserts become cyclonic. But dustwhirls occur in all parts of a uniformly heated plain and are not limited to a single zone except where this is determined by the internal composition of the plain itself. In similar fashion in the sun, unless there is some special aggregation of matter in two bands about 10° to 30° from the equator, we should expect the cyclonic movements due to cooling to occur in all parts of the atmosphere. This is what we actually find in the rice grain structure. It is often supposed that the solar atmosphere rises in the bright spots, while the intervening dark spots are places where gases that have previously risen have cooled and are sinking. Even if this is not the exact mechanism of movement, the rice grains with their uniform distribution all over the sun appear to represent the kind of convectional circulation which we should expect in a cooling body of gas like the sun. There is no conspicuous zonal distribution, no violence, no periodicity, and no gradual change of latitude. The fact that the sun appears actually to have the type of circulation which we should expect on the basis of the physical structure of its atmosphere suggests that the other and more violent type may be of external origin.

Let us now turn to external agencies and see whether there is any evidence that they are connected with sunspots. Planets, comets, and other stray bodies are the only known outside agencies that exert a rapidly varying effect upon the sun. Of course the great gravitative pull of the entire universe is not to be neglected, nor is the attraction or radiation of individual stars and of the non-luminous matter scattered through space, but these conditions are not known to vary in any appreciable way from year to year, though they may vary greatly in longer periods. Hence let us turn to the planets as the most important variables now known to be acting on the sun. Comets and similar bodies may be omitted for the present.

The planets fit the elements of our problem in two main respects, namely, in their location with reference to the equator and in their periodicity. To begin with location; the orbits of the planets all lie in essentially the plane of the sun's equator, as appears in Table 36 in Chapter XIII. Nevertheless, they depart from this somewhat. The earth, for example, when viewed from the sun, moves back and forth through 14½° of latitude; that is, 7¼° on each side of the sun's equator, just as the sun when seen from the earth moves through 23½° on each side of our equator. The other planets move similarly back and forth across the sun's equator, but with slightly different amplitudes because of differences in the planes of their orbits. A complete movement of each planet from its most southerly to its most northerly position and back again takes anywhere from 88 days, in the case of Mercury, to 165 years in that of Neptune.

The constantly shifting position of the planets because of the inclination of their orbits to the sun's equator means that one planet or another is nearly vertical to the sun's equator most of the time, while at all parts of a zone extending roughly seven degrees on each side of the equator, a planet is occasionally in the zenith. If the planets heated the sun as the sun heats them, they would produce an equatorial zone of low pressure on either side of which there would be subtropical belts of high pressure. As a matter of fact, the sun's equatorial belt of few or no spots corresponds to the area where the planets are vertical, but this is presumably due to Ferrel's law whereby cyclonic disturbances are damped at the equator.

The relation of the periodicity of the planets to solar disturbances is so important a topic that it is worth while to trace some of the chief steps in its development. As long ago as 1859, Wolf,[6] who is famous as the first to prepare the sunspots tables which are now so widely used, advanced the idea of a connection between sunspots and planetary tides. He computed a formula by which the mass, distance, and angular position of the planets may be used to produce a curve agreeing in its main outlines with that of the sunspots. A few years later De la Rue, Stewart, and Loewy[7] published a most suggestive paper which has been neglected because of the later mistakes by one of the authors, but which Schuster, Puiseux, and others regard as pioneer work of much importance. They show that during the years 1854-1860 and 1862-1866, sunspots were larger on the side of the sun turned away from Venus and Mercury than on the side turned toward them. For Jupiter, on the other hand, they find two maxima approximately 90° from the planet's meridian. These facts suggest that the sun's rotation would cause variations in its spottedness even if its position with respect to the planets remained otherwise unchanged.

Without attempting to mention all who have studied the matter, let us turn to Birkeland's[8] exhaustive study. In spite of his theory that sunspots resemble volcanoes,

[6] R. Wolf: Academie des Sciences, Paris, Comptes Rendus, Vol. 45, 1859, p. 231.

[7] W. De la Rue, B. Stewart, and B. Loewy: Further investigations on planetary influence upon solar activity, Proc. Roy. Soc., Lon., Vol. 20, 1872, pp. 210-218.

[8] Kr. Birkeland: Recherches sur les taches du Soleil et leur origine, Skrifter udvigne af Videnskabsselskabet, I, Christiania, 1899.

he concludes that the tidal action of the planets is an important element in causing the release of the sun's internal energies. Instead of studying the effect of the sun's rotation, he investigated the relation of sunspots to the revolution of the planets around the sun and to their varying distances from the sun and the degree to which their angular position causes them to act together or in opposition. For our present purpose his main contribution is a table and graph showing the relation between sunspots and the combined tide-making force which Jupiter, the earth, and Venus exert on the sun. The graph represents the amount by which the tide-making force at any given moment exceeds the minimum tide-making force of the three combined when each is farthest from the sun at aphelion. Each main rise in the tidal line is followed by a sunspot maximum in two to six years. In the parts of the curve from 1840 onward one can detect not only major maxima of sunspots following major maxima of tidal forces, but also many minor correspondences.

In earlier years the agreement is not so close as later, and in 1819 a tidal maximum is followed at an interval of three years by a sunspot *minimum*. Hence, while a certain relationship is suggested, there is also evidence that, even if it is real, there is some other factor at work. It is noticeable that the apparent relationship is strongest when the sunspots are most numerous and becomes weak at times when the sunspot minima are low.

Another study along the same lines has been made by Brown,[9] but instead of using Jupiter, the earth, and Venus, he used Jupiter and Saturn. Because of the eccentricity of its orbit, Jupiter's tide-making force is 0.33

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[9] E. W. Brown: A Possible Explanation of the Sunspot Period, Monthly Notices, Roy. Astron. Soc., Vol. 60, 1900, pp. 599-606.

Resultant of Periods 11·86, 9·93

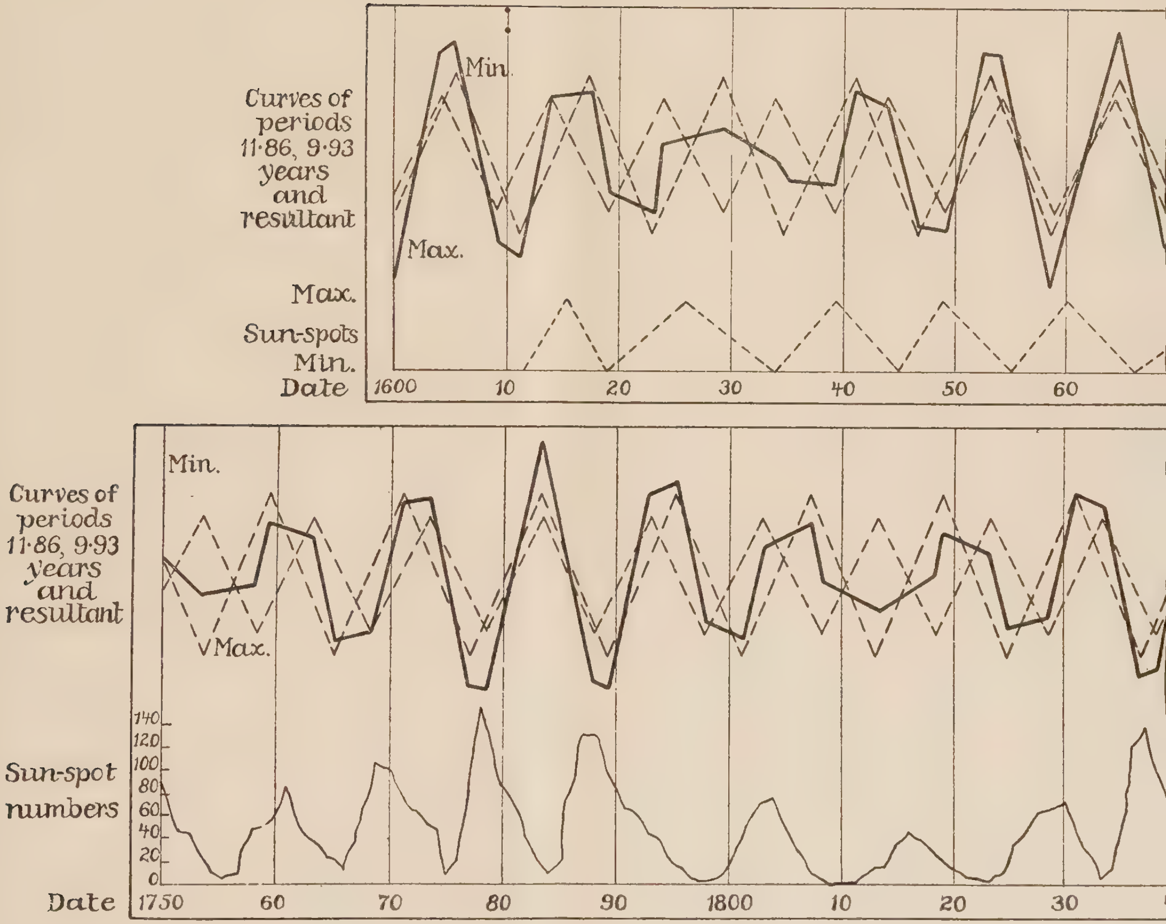
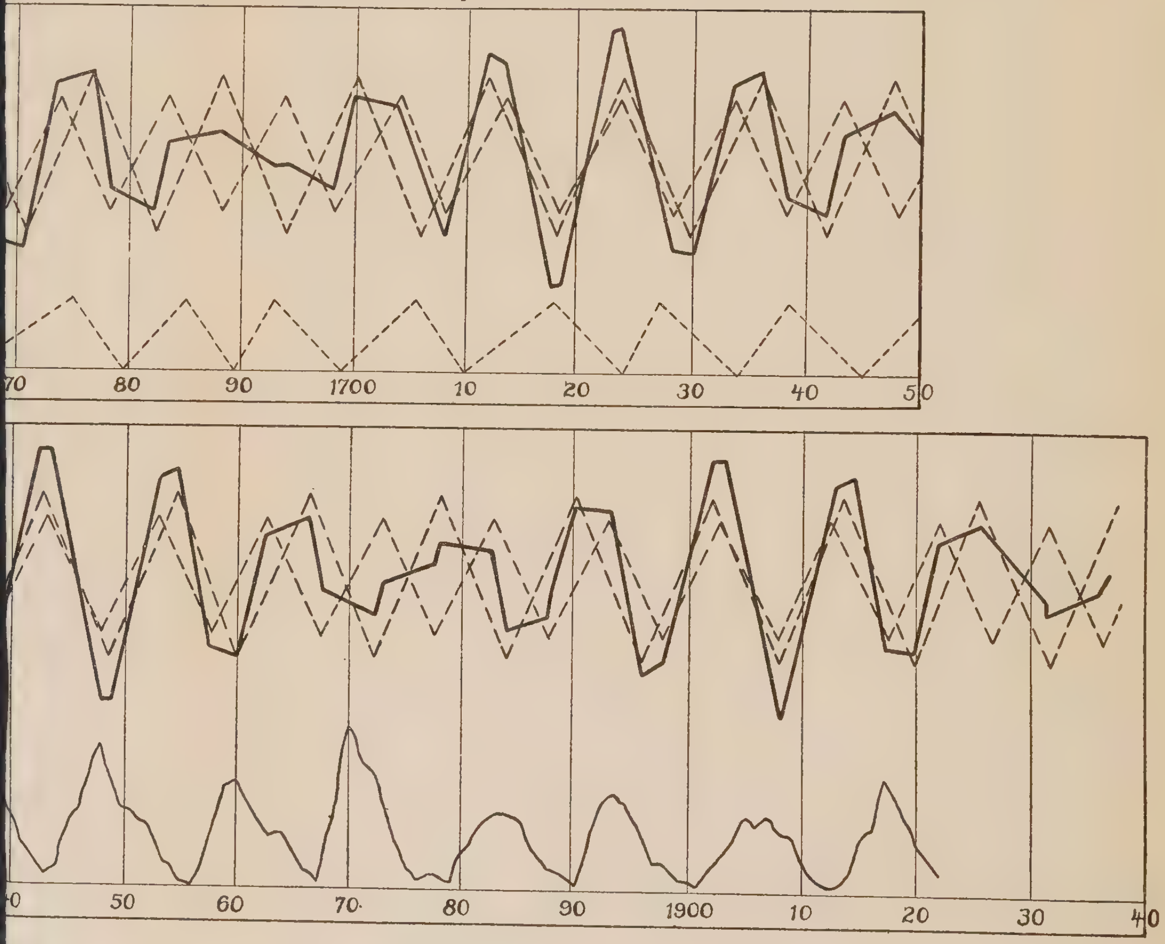


Fig.

Brown's Comparison of Sunspot Periods with the Period Resulting from Jupiter's Period (11.8

years, compared with Sun-spot Periods



41.

years) and the Period of Jupiter's Opposition and Conjunction with Saturn (9.93 years).

above the average at perihelion and 0.33 below the average at aphelion, the earth's tide-making force on the sun being taken as unity. Saturn's variation because of the eccentricity of its orbit is negligible, for its total tide-making force amounts to only 0.11. This total tide-making force is added to Jupiter's force when the two planets are in the same direction from the sun and also when they are on opposite sides, since there are always tides on both sides of a body disturbed by gravitation. It is subtracted from that of Jupiter when the two planets are at right angles. Thus, when Jupiter and Saturn work together, the tide on the sun may be 0.44 more or less than normal. On this basis, Brown has drawn Fig. 41, showing the combined effect of Jupiter and Saturn. In its main outlines the curve resembles Birkeland's, but with marked differences. It will be noticed that Brown has inverted his planetary curve so that the maxima come at the bottom. When compared with the sunspot curve it shows a repeated occurrence of planetary maxima a little before sunspot maxima, or almost coincident with such maxima, especially when the variations from the normal are strongest. The most noteworthy features are (1) the way in which the curves cease to harmonize closely at times like the end of the last century when the sunspot maxima are low, and (2) the way in which the two curves keep coming back into harmony whenever sunspots become especially numerous. This was true in 1848, 1837, 1788, and 1779. It also appears in 1718 and 1648. In the earlier years, where the sunspot curve is dotted, we have data only as to the years of maxima and minima and not as to the actual sunspot numbers. Moreover, our information as to the exact dates of maxima and minima is not reliable, so that a discrepancy such as the occurrence of the spot maxima of 1694 and 1706 before the planetary maxima of 1698 and 1708 would have little significance even if there were no accidental causes which might give rise to it. In the 170 years since 1750, for which there are fairly reliable data, each curve shows 15 maxima. When the planetary influence is weak the sunspots seem to lag behind, but catch up when it is strong, that is, when Jupiter is in perihelion at the same time that it is near Saturn. Hence, the agreement shown by Brown's curve between sunspots and tidal forces is close enough to suggest a relationship, although there are certain discrepancies. It is noteworthy, however, that this curve based on Jupiter and Saturn shows agreement with the main sunspot cycles, while Birkeland's curve based on Jupiter, the earth, and Venus shows agreement with many of the minor cycles.

The degree of agreement between Brown's curve and the sunspot curve may be judged from the fact that when no allowance is made for lagging, the direct correlation coefficients are as follows:

TABLE 23

CORRELATION COEFFICIENTS BETWEEN SUNSPOTS AND COMBINED EFFECT OF JUPITER AND SATURN

Years	r *Correlation coefficient*	e *Probable error*	r/e *Ratio of coefficient to probable error*
1750-1800 A. D.	+0.380	±0.082	4.6
1801-1850 A.D.	+0.578	±0.063	9.2
1851-1900 A.D.	+0.405	±0.080	5.1
1750-1900 A.D.	+0.457	±0.043	10.6

In every case the coefficient is positive and is at least 4 times the probable error. For the entire period from 1750 to 1900 the coefficient rises to more than 10 times the probable error, and if later years are added this is increased still further. According to the generally accepted laws of correlation this is enough to establish a relationship. It literally means that there is only one chance in billions of billions that the apparent resemblance of the curves is accidental.

The most remarkable feature of Brown's curve still remains to be mentioned. He published his article in 1900 at a time when the sunspot numbers were low. His curve then deviated so much from the sunspot curve that he was doubtful as to the agreement between the two. By means of his method I have continued the Jupiter-Saturn curve to cover the period that has since elapsed. The sunspot maximum of 1905-1906 again comes into close harmony with Brown's curve, while in 1917 the agreement is still closer. Thus Brown's work published in 1900 provided a basis by which, as Clayton puts it, the two succeeding maxima might have been predicted with great accuracy. It remains to be seen whether the prediction will continue to hold good, but a successful prediction for twenty years is no small matter. Nor will a future failure to find exact agreement prove the method wrong, for almost certainly Jupiter and Saturn are not the only factors in determining the periodicity of sunspots. The other planets must be considered and perhaps some of the nearer stars or other heavenly bodies, as I have suggested in *Climatic Changes.*

One of the next investigations in point of time was that of Mrs. Maunder,[10] who like De la Rue and Stewart based her work on the sun's rotation with respect to its satellites. She studied the relation of solar activity to the earth as indicated by the number of sunspots during the sunspot cycle from 1889 to 1901. She shows that during that period sunspots were more numerous on the east side of the sun's visible disk than on the west side. In other words, when the sun's rotation brings new parts of the solar disk into the earth's field of view, those parts bear rather more than the average number of spots. The excess of spots on the eastern side of the sun is greatest about 45° from the eastern edge of the disk. The earth seemingly causes the number of sunspots to diminish, and Mrs. Maunder came to this conclusion. This, however, may be a mistake, for she made no allowance for the fact that a great disturbance such as a sunspot must lag behind its cause. The important point, however, is that her results for the earth agree with those of De la Rue, Stewart, and Loewy for Venus and Mercury. They seem to be too consistent to be the result of chance.

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[10] A. S. D. Maunder: An apparent influence of the earth on the numbers and areas of sunspots in the cycle 1889-1901, Monthly Notices, Roy. Astron. Soc., Vol. 67, 1906-1907, pp. 451-479.

More recently Pocock[11] has made a similar investigation for a later period than Maunder's, namely, 1902-1917. He obtains the same result, an excess of spots on the east side of the sun's visible disk. It should be noted, however, that the excess is greater when the *number* of spots is considered than when their *area* is taken into account. This means that the earth's effect, if such there be, is more marked in producing small spots than in increasing the area of large ones. Again, the apparent effect of the earth is quite noticeable when sunspots are increasing or diminishing, but disappears during the years near maximum and minimum. Prominences are found by both Maunder and Pocock to behave in essentially the same way as sunspots; that is, they appear to diminish in number under the influence of the earth. The full significance of all these facts is apparent when we remember that a given area of the sun's visible disk, such as the eastern edge, is not a particular part of the sun but merely a *position* which every part of the sun's surface occupies at some time during each solar rotation. An excess or deficiency of spots in such a position, if it is real, must be due to some terrestrial influence and not to anything in the sun.

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[11] R. J. Pocock: The relative numbers and areas of sunspots east and west of the central meridian during the years 1902-1917, Monthly Notices, Roy. Astron. Soc., Vol. 79, November, 1918, p. 54.

Another investigation along this line has been made by Schuster.[12] Using only the new spots reported on the daily photographs, he finds that during the 36 years from 1874 to 1909, Mercury, Venus, and Jupiter all appear to have an influence on the number of sunspots. His results are summed up in Fig. 42. This shows the number of new spots appearing on different parts of the sun's surface when such parts are in various positions with reference to the planets. The point half way between 12 and 1 at the right side of the diagram represents the part of the sun's surface directly away from the planet, that is, midnight as we should call it if we were on the sun and the planet were illuminating us. In the same way a point between 3 and 4 represents that part of the sun's surface where the planet is just rising, noon falls between 6 and 7, and ''planet-set'' between 9 and 10. The noteworthy features of the diagram are the minima in all the lines at 3, that is, just before sunrise, and the main maxima at 8, that is, about 3 p.m. as it would be in terrestrial terminology. Of course the solar ''day'' is from 25 to 30 times as long as that of the earth. Less important features are the minor maximum in the morning and the minor minimum toward noon. When full allowances are made for all sorts of contingencies, Schuster concludes that the probability that we are being misled by an accidental coincidence is only about one in 400,000.

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[12] A. Schuster: The Influence of the Planets on the Formation of Sunspots, Proc. Roy. Soc., Lon., Vol. 85, 1911, pp. 309-323.

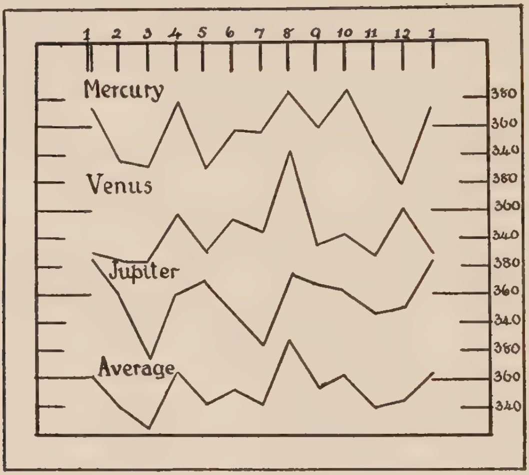

Fig. 42.

Schuster's Diagram of the Relation of Sunspots to the Solar Longitude of the Planets.

Although there are some discrepancies between the results of De la Rue, Maunder, and Pocock on the one hand, and Schuster on the other, all agree as to the reality of a planetary effect on sunspots. The discrepancies appear to be due to the fact that the various investigators used different areas and different methods, and also to the fact that different portions of the sunspot cycle act differently, as shown by Pocock. They may also be due in part to the way in which spots, because of their bipolarity, reverse their signs sometimes at sunspot minima. The whole matter needs further intensive study, but this much is clear; each of the methods thus far described gives consistent results for two or more planets, or for two or more sunspot cycles. The chances that this could happen by accident are much less than 1 in 400,000, for that applies only to Schuster's results.

CHAPTER XI

THE SUNSPOT PERIOD AS A RESULT OF PLANETARY INFLUENCE[1]

BY HENRY HELM CLAYTON

VERY soon after the discovery of the sunspot period by Schwab, the suggestion was made by R. Wolf that the period was perhaps the result of planetary influence, since the period corresponds roughly to the orbital period of Jupiter, the giant planet of the solar system. Since then numerous writers have maintained this view; but later observations have appeared to indicate that the period is shorter than the orbital period of Jupiter, which is 11.86 years.

A second hypothesis was then suggested, namely, that the period arises from internal strains in the solar mass which take a certain time to accumulate to the breaking strain, when there follows a commotion in the sun's mass tending to restore equilibrium, a process which assumes the more or less rhythmical character known as the sunspot period.

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[1] This chapter in certain respects duplicates what is said in the chapters that precede and follow it. Nevertheless, when I found that Mr. Clayton had independently come to many of the conclusions that I had reached, and that this had happened without either of us knowing what the other had done, it seemed to me worth while to insert his results just as he wrote them before he had read any other part of this book. The way in which he has been led to carry on investigations parallel to my own and yet supplementing rather than duplicating them makes his book on *World Weather* essential to anyone who finds the present book worth reading. Since both of us came independently to the same conclusion as to the importance of solar variations in controlling the weather, it was only natural that both should investigate the causes of the periodicity of sunspots. The agreement of the results along this line strengthens the conclusions of both. I am greatly indebted to Mr. Clayton for his kindness in putting his results at my disposal.

It is not yet possible to prove or disprove this latter hypothesis. It is, however, entirely conceivable that a large mass may be subject to a great strain which brings about slow movements, and that comparatively small additional strains, like those due to the gradually increasing tidal action of a planet as it approaches the sun in an elliptical orbit, may then determine the time of release of the internal strains and thus determine periodic oscillations in the eruptive processes on the sun.

This point of view, although long more or less hazily maintained, was given impetus by certain researches of Schuster suggesting planetary influences in solar variations, but more especially by the careful calculations of Chamberlin and Moulton. They showed that any body of considerable mass passing near the sun in a parabolic or elliptical orbit would initiate tidal strains in the sun, causing matter to be ejected outward from the solar mass, both in the direction of the passing body and also in the opposite direction. This process is illustrated by Fig. 43. A body moving along the line S^1-S^2 would cause matter to be ejected outward along the lines P^1 and P^2. Chamberlin says that

> in accordance with well-known tidal principles one set of the eruptive prominences must have been shot directly toward the passing star and the other set in the opposite direction. . . . The realities of the case are beyond question. . . . The outshoot toward the passing star should be a little greater than the outshoot on the other side of the sun.[2]

In the light of these possibilities, it seems well worth while to examine anew the question of planetary influence upon the solar changes indicated by variations in the spottedness of the sun. In 1916 the writer began an investigation of this kind and was much aided by the assistants at the Argentine Meteorological Office in making the necessary calculations.

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[2] Chamberlin, T. C.: The Origin of the Earth, University of Chicago Press, Chicago, 1916, pp. 112-113.

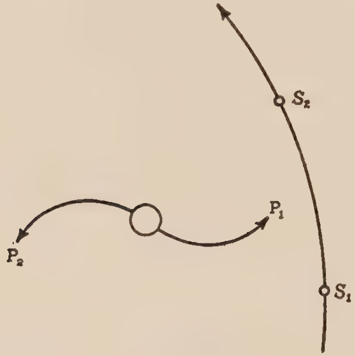

Fig. 43.

The Lines of Tidal Disruption.

That the sunspot period as shown by the latest observations is not widely different from the period of Jupiter's orbital period may be seen from Fig. 44, in which an harmonic curve shows the approach and recession of Jupiter in relation to the sun. The letter P in the harmonic curve shows the time when Jupiter was nearest the sun (perihelion) and the letter A the time when it was farthest away (aphelion). Beneath the Jupiter curve is the sunspot curve plotted from the sunspot numbers of Wolfer. The oscillations of these curves during the past half-century are in almost perfect unison, the perihelion (P) of Jupiter being about two years in advance of the sunspot maximum and the aphelion (A) being about three years in advance of the sunspot minima.

Another way of visualizing the relation of the sunspot changes to the period of Jupiter's revolution is to plot the sunspots in 12-year periods, one above the other, so that the maxima and minima come in a series. This arrangement is shown in Fig. 45, where the date of the beginning of each 12-year period is shown on the left, and the sunspot scale on the right. It is seen from this plot that the sunspot period is less than 12 years, because the maximum and minimum of each successive period tend to fall to the left of the preceding maximum and minimum. The broken lines A, B, and C show the period of Jupiter (11.86 years), which evidently is not widely different from the sunspot period back as far as 1836. The position of the line A indicates the time of the perihelion passage of Jupiter, the line B, two years later, shows approximately the time of the sunspot maxima, and the line C, nine years later than A, shows the approximate time of the sunspot minima.

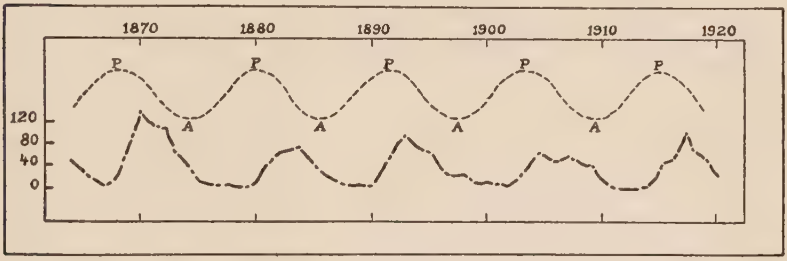

Fig. 44.

The Orbital Period of Jupiter compared with the Sunspot Period.

But if Jupiter influences solar activity, it is probable

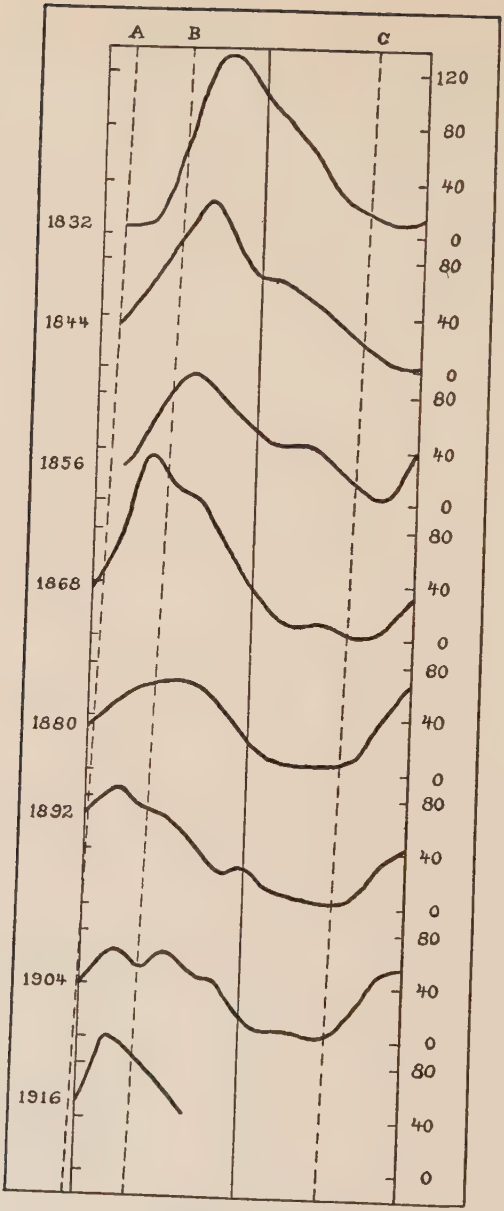

Fig. 45.

Sunspots by Twelve-year Periods.

that other planets do the same in a lesser degree. In that case, the sunspot period results from the combined influence of all the planets and it should not be expected to follow the Jupiter period exactly.

If the planets influence solar eruptions in the manner suggested by Fig. 43, at least three factors would join in determining the amount of strain exerted on the solar mass, namely, (1) the eccentricity of the planet's orbit, (2) the mass of the planet, and (3) the distance of the planet from the sun, the influence being proportional to the inverse square of the distance. Table 24 gives these three factors in terms of the earth as unity. Line 4 of the table gives the inverse square of the relative distance, that is, unity divided by the distance squared. The product of the relative eccentricity, mass, and inverse square of the distance may be taken as an index of the relative influence of each planet in disturbing the sun. From this viewpoint Jupiter has by far the predominating influence, with a relative number of 35.5 in line 5, and is

TABLE 24

RELATIVE MEASURES OF PLANETARY ACTION; EARTH=1

	Mercury	*Venus*	*Earth*	*Mars*	*Jupiter*	*Saturn*
(1) Eccentricity	12.1	0.4	1.0	5.5	2.8	3.3
(2) Mass	0.03	0.84	1.00	0.11	317.0	95.0
(3) Distance	0.39	0.72	1.00	1.52	5.20	9.54
(4) $\frac{1}{(\text{distance})^2}$	6.9	1.9	1.0	0.5	0.04	0.01
(5) Product of (1), (2), and (4)	2.5	0.6	1.0	0.3	35.5	3.2
(6) Product of (2) and (4)	0.2	1.6	1.0	0.1	12.7	1.0

followed by Saturn, with a relative number of 3.2, by Mercury, with a relative number of 2.5, and by the Earth, with a relative number of 1.0. The index numbers for Venus and Mars are so small as to be negligible.

Another way in which the planets might produce strains in the sun is by their conjunctions and oppositions. In that case the eccentricity would be of small importance and the product of the mass by the inverse square of the distance may be taken as an index of the effect of the planets on the sun. This product is shown in the last line of Table 24. From this point of view Jupiter still has by far the greatest weight, then come Venus, Saturn, and the Earth. The conjunction or opposition of Jupiter and Saturn, however, is of greater importance than any other because the interval from conjunction to opposition is long, and while the two planets are near conjunction or opposition the rapid revolution of both Venus and the Earth must cause their influence to unite with that of the large planets at relatively short intervals.

There are, then, at least eight periods worth examining in investigating the question of planetary influence on the sun:

(1) The period of Jupiter's orbital movement (11.86 years).

(2) The period of Saturn's orbital movement (29.45 years).

(3) The period of Mercury's orbital movement (87.97 days).

(4) The period of the Earth's orbital movement (1 year).

(5) The period of the conjunction of Jupiter and Saturn (19.86 years).

(6) The period of the conjunction of Jupiter and Venus (236.72 days).

(7) The period of the conjunction of Jupiter and the Earth (398.95 days).

(8) The period of the conjunction of Venus and the Earth (582.93 days).

One way of determining the relative importance of each period is to divide all the sunspot data into periods of the length of the suspected periods and obtain averages of the sunspot numbers during the different parts of the periods. This has been done for the first five of the periods mentioned above as well as for the orbital period of Venus. The results for the planets are given in Table 25 and Fig. 46, with the perihelion at the left end of each curve. It is seen that (1) a maximum of sunspots follows the perihelion passage of every one of the planets; (2) this maximum occurs when each planet has traversed about one-third of its orbit after the perihelion passage; and (3) the intensity of the effect is approximately in the order of the product of (1), (2), and (4) in Table 24. The apparent exception in the case of Mercury is due to the large part of the orbital period (one-third) covered by the smallest unit (one month) in the sunspot data. Had the subdivisions been smaller, the results for Mercury would presumably fall between those of Saturn and the Earth. In Fig. 46 the space occupied by each period is the same, that is, the long period of Saturn is made to occupy the same space as the period of Jupiter and of Mercury. In the case of Saturn, on account of the small number of times (6) that the period has repeated itself during the interval covered by the sunspot data (1749-1920), the curve based on the crude averages of the six periods was irregular and has been smoothed by getting overlapping means of ten years. In the case of the smaller planets the number of periods was so great that the averages were not extended back to the beginning of observations, but cover the interval from 1856 to 1912. Within this interval there were 232 periods of Mercury, 76 of Venus, and 57 of the Earth. The means were derived from deviations from yearly means and hence have plus or minus signs in Table 25.

Table 25 indicates that the orbital period of Jupiter is by far the most effective in causing changes in the amount of spottedness on the sun.

In order to study this apparent effect more in detail,

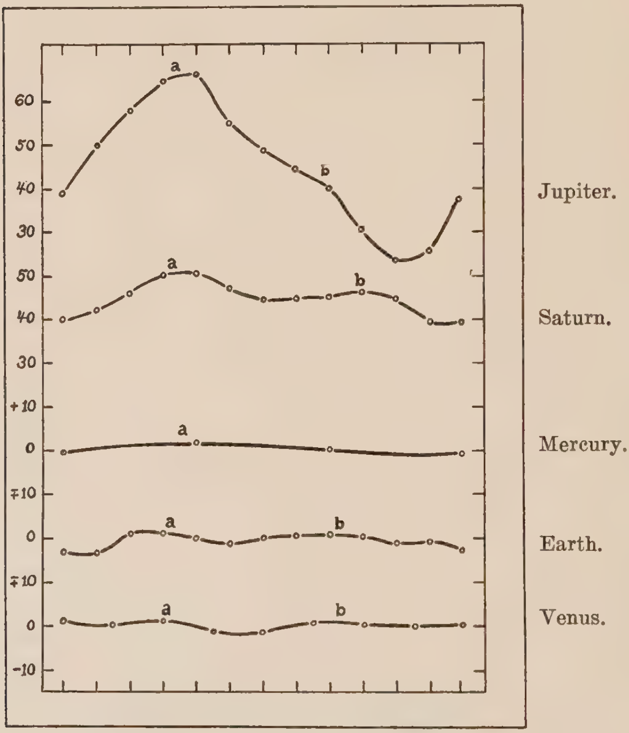

Fig. 46.

Sunspots during Sidereal Periods of Planets. See Fig. 51.

TABLE 25

AVERAGE YEARLY OR MONTHLY NUMBER OF SUNSPOTS FOLLOWING PERIHELION PASSAGE OF VARIOUS PLANETS

JUPITER

Years after perihelion	0	1	2	3	4	5	6	7	8	9	10	11
Sunspot numbers	38	49	57	64	*66*	55	49	44	40	31	24*	26

SATURN

Years after perihelion	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14
Sunspot numbers	32	37	58	57	59	46	42	39	41	48	70	68	61	53	48
Mean of 10 years	40	40	41	42	43	46	48	51	*51*	51	50	49	48	46	45
Years after perihelion	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29
Sunspot numbers	43	28	23	24	45	58	64	66	57	46	42	37	30	25	22*
Mean of 10 years	44	45	45	45	46	45	45	46	47	47	45	42	39	39*	39

MERCURY

Months after perihelion	0	1	2
Sunspot numbers	—0.5	+1.5	0.0

EARTH

Months after perihelion	0	1	2	3	4	5	6	7	8	9	10	11
Sunspot numbers	—2.8	—3.3	+1.5	+1.6	+0.1	—0.4	+0.2	+1.3	+1.4	+0.9	—0.4	—0.6

VENUS

Months after perihelion	0	1	2	3	4	5	6	7
Sunspot numbers	—1.0	+0.0	+0.5	—1.3	—2.2	+0.9	+1.2	+0.1

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* In the case of the Earth 0 month is December, 1 is January, etc.

it is desirable to free it, in so far as may be, from the influence of the other planets. The periodic influences attributable to the smaller planets may be diminished and largely excluded by taking means of 12 monthly values of the sunspots. This has been done by Wolfer and his overlapping means of 12 months were used as the basis of the investigation. Since five periods of Jupiter (59.30 years) are equal to two periods of Saturn (59.35 years) the influence of Saturn both as regards its orbital period and its conjunction period can be largely eliminated by getting means of each five successive periods of Jupiter. This has been done and the results are given in Table 26.

This table shows that the mean position of the time of

TABLE 26

AVERAGE MONTHLY NUMBER OF SUNSPOTS IN EACH SUCCEEDING FIVE PERIODS OF JUPITER

(From Wolfer's relative sunspot numbers)

*Date**	*Perihelion*	*Years after*										
	0	*1*	*2*	*3*	*4*	*5*	*6*	*7*	*8*	*9*	*10*	*11*
1773.99	49	45	50	50	*64*	59	56	58	59	48	37	32
1785.85	31*	34	41	43	*63*	60	60	63	58	44	29	20
1797.71	19*	25	32	40	*63*	62	60	59	49	39	25	16
1809.57	14*	25	38	53	*65*	57	55	57	46	37	25	16
1821.43	11*	14	25	54	*64*	56	56	58	47	35	24	14
1833.29	12*	20	38	70	*75*	61	58	56	47	35	24	16
1845.15	22	40	66	89	*93*	69	59	50	41	31	20	15*
1857.01	28	51	77	*101*	101	72	53	40	29	19	10*	17
1868.87	40	66	84	*93*	80	55	41	28	23	14	8*	19
1880.73	43	69	*81*	79	68	48	33	18	14	9	7*	27
1892.59	52	82	*82*	73	58	..	..	..	..	..	..	..

* The data given in the first column of the table are the mean dates of the five periods and are also the dates of the perihelion of Jupiter.

maximum sunspots in the Jupiter period occurred with wonderful constancy in the fourth year after Jupiter's perihelion during the first 70 years of observation, but about 1840 the maxima began to shift into the third or even the second year, indicating a shortening of the period.

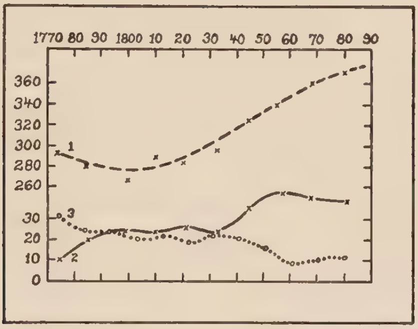

Fig. 47.

Harmonic Analysis of the Sunspot Period.

In order to study the question in another way the data were subjected to harmonic analysis and the phase angle and amplitude were computed for the first harmonic in each period shown by the data in Table 26. The results are plotted in Fig. 47. In this figure curve No. 1 shows the changes in azimuth during the periods from 1770 to 1880 and curve No. 2 shows the changes in the amplitude of the oscillations.

The regular sweep of curve 1 showing the change in azimuth suggests a long oscillation in the length of the Jupiter period, an oscillation which requires nearly 200 years for its completion. The minimum azimuth was reached about the year 1800, after which there was a sweep upward. This apparently culminated about the year 1900, for the mean interval between successive maxima is now almost exactly the same as the orbital period of Jupiter, as may be seen from Fig. 45. Curve 2 in Fig. 47 giving the amplitude of the Jupiter period shows that the amplitudes were small when the azimuth values were near minimum and increased as the azimuth curve swung upward. The reason for this long periodic swing in the length and amplitude of the Jupiter period is not apparent; but when a sufficient period of observation has expired to determine the length of the swing, some explanation will probably be found.

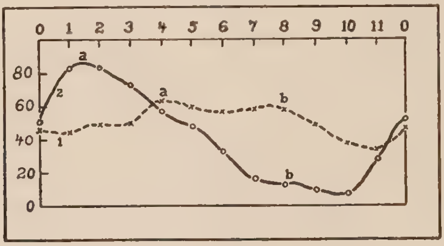

Fig. 48.

Mean Sunspot Curves during the Sidereal Period of Jupiter's Revolution.

Coincident with the change of amplitude there has been a change in the form of the curve representing the period. In Fig. 48 curve 1 is a plot of the mean of the sunspot numbers during the first five of the periods of Jupiter and centers about 1770; curve 2 is a plot of the last five centered about 1890. In the first plot there are two maxima, the primary maximum occurring about four years after Jupiter's perihelion, and the second about four years later. The Jupiter curve thus resembles the curves of Saturn, the Earth, and Venus plotted in Fig.

46. As the amplitude of the variations in spottedness during the Jupiter cycle increased, the primary maximum approached nearer to the perihelion passage of Jupiter and the secondary maximum disappeared. This tendency for the more marked maxima to approach the time of perihelion is clearly seen in the plot of the individual periods in Fig. 45 in which the time of perihelion is shown by the broken line A. The most marked maxima of recent years like those of 1870 and 1917 followed very close after the perihelion of Jupiter (about one year); while the less marked maxima like those of 1883 and 1906 lagged several years behind.

Having tested the orbital periods of the various planets and found evidences of a relation to sunspots, let us next test the periods of conjunction and opposition. For this purpose Wolfer's sunspot numbers have been divided into periods of the length of the conjunction period of Jupiter and Saturn (19.8587 years), and means have been obtained for each three of the periods, thus approximately eliminating the orbital periods of Jupiter and Saturn. The results are given in Table 27.

This table indicates that the conjunction period of Jupiter and Saturn is correlated with an oscillation in the number of sunspots, and that this is almost as important as the oscillation corresponding to the orbital period of Jupiter. The principal maximum is two years before the conjunction of the two planets and there is another maximum of less marked intensity four years before opposition. If these two maxima be taken as indicating a period of slightly less than ten years there will be in 59.5 years six conjunction and opposition periods of Jupiter and Saturn and five orbital periods. The harmonic analysis shows that from 1770 to 1890 the phase angles and amplitude of the conjunction-opposition period moved inversely to those of the orbital period of Jupiter. The amplitudes of the ten-year period are

TABLE 27

MEAN MONTHLY NUMBER OF SUNSPOTS FOR EACH YEAR OF THE CONJUNCTION PERIODS OF JUPITER AND SATURN

	Conjunction										*Opposition*									
		Years after maximum																		
			□									☍								
Date	*0*	*1*	*2*	*3*	*4*	*5*	*6*	*7*	*8*	*9*	*10*	*11*	*12*	*13*	*14*	*15*	*16*	*17*	*18*	*19*
1770.11	*106*	76	62	48	32	19	14*	26	64	*66*	59	58	53	43	35	28*	32	50	67	72
1789.96	*76*	58	48	34	32	21*	21	24	*62*	60	46	38	33	27	19*	23	32	53	66	66
1809.82	*60*	48	41	31	23	20*	33	59	*65*	50	39	35	29	24	20*	24	28	36	43	68
1829.66	*59*	48	42	32	23	17*	31	53	*66*	60	61	61	47	32	24	22*	29	36	43	65
1849.52	92	*94*	76	64	36	24*	25	40	56	51	57	*68*	64	50	48	38	41	33	30	51
1869.39	73	75	71	*78*	61	47	31	19	15*	21	36	47	*50*	44	49	47	51	34	28	24
1889.23	50	58	50	*59*	47	41	42	36	46	36	29	29	..	..	..	..	..	..	..	..
Mean 1750-1920	*72*	60	52	46	34	26*	29	38	*59*	54	50	49	40	36	34	31*	37	42	51	60

shown by the dotted line (3) in Fig. 47 and it is seen that from 1770 to 1830 the amplitudes of the conjunction-opposition period were as great as those of the orbital period but decreased as the amplitudes of the orbital period increased. For the whole interval of 172 years (1749-1920) the mean orbital period (11.86 years) shows a range of 42 sunspot numbers, while the mean conjunction-opposition period (9.93 years) shows a range of 33 spot numbers.

The amplitudes of the various periods computed by harmonic analysis from the mean values are:

(1) Orbital period of Jupiter,[3] 19.1;

(2) One-half conjunction period of Jupiter and Saturn, 14.5;

(3) Orbital period of Saturn, 6.2;

(4) Corrected amplitude of the orbital period of Mercury, 2.0;

(5) Orbital period of the Earth, 1.2.

The conjunction periods of Jupiter and Venus and of the Earth and Venus have not been investigated in detail by the writer, but others have found periods approximating these lengths. By means of the Schuster periodogram, Elsa Frenkel[4] investigated the possibility of short periods in sunspots and found a period of about 200 days, which is half of the conjunction period of Jupiter and the Earth, thus indicating a maximum of spots at conjunction and at opposition as in the case of Jupiter and Saturn.

A third class of possible tidal effects is the result of the rotation of the sun on its axis by reason of which to an observer on the sun the planets would appear to rise, pass across the sky, and set, and thus produce tidal

[3] The amplitude of the 11-year sunspot period is 17.6.

[4] Elsa Frenkel: Untersuchungen über Kurzperiodische Schwankungen der Haufigkeit der Sonnen flecken, Pub. der Sternwarte des Eidg. Polytechnikunst zu Zurich, Bd. V, s. 47.

strains in the surface of the sun just as the moon produces tidal strains in the surface of the earth. Possible effects in the sun due to this relation of the sun and planets have been investigated by De la Rue, Maunder, and Schuster, all of whom have found results which seem more than mere accidental relations.

The question now arises as to whether the planets are capable of producing gravitational strains in the sun of sufficient importance to produce appreciable effects. Schuster considered this question and assuming conditions in the solar surface such as modern research renders probable, he estimates that the tidal strains exerted by the earth on the sun are approximately of the same order of magnitude as that of the moon on the earth.[5]

The question of the method by which tidal strains may produce eruptions on the sun has been considered by T. C. Chamberlin in his book on *The Origin of the Earth* (Chicago, 1916), pp. 110-112. He says:

> Let it be recalled that such a tidal response takes the form of ''bulges'' on opposite sides, one toward the attracting body, and one on the opposite side. Between these ''bulges'' and at right angles to their axis there is a girdle of tidal compression arising from a component of the oblique attraction exerted on these parts by the tide-raising body.
>
> If the lifted portions that form the ''bulges'' were plotted as though lifted from a plane instead of a spheroid, they would appear as cones. Such conical forms would represent truly the way in which the lifting force of the tidal pull is distributed over the tide-lifted area. The bulging form, as we style it, arises from the curved base on which the lifted portions are superposed. There is a certain merit, therefore, in the use of the term tidal cones, rather than tidal bulges.
>
> Picture the passing star, therefore, as having eased by its dif-

---

[5] The quotation from Schuster is given in full on a later page.

> ferential attraction the internal pressure of the sun along the axis of the tidal cones, while it has added to the pressure at right angles to them. Under the law of least resistance, it is clear that this would have predisposed the eruptive forces within the sun to ease themselves along the lines of this reduced pressure, rather than in directions of higher pressure. Any previous tendency to eruption at right angles to the axes of the cones would necessarily feel the restraint of the increased pressure in those directions. There would, therefore, be a concentration and intensification of the eruptive action in the axes of the cones and a restraint and reduction elsewhere. Even now, owing to causes not yet determined, the eruptive action in the sun is concentrated in certain sub-equatorial belts. It is also subject to periodic fluctuations. Both of these indicate its susceptibility to concentration. There is, therefore, firm ground for the inference that the eruptive action under the conditions sketched would have centered in the tidal cones, and would have been much more massive and more forceful than under normal conditions.

Chamberlin in this quotation was considering the effect of a passing star, but there seems no reason why his reasoning does not apply equally well to the differential tidal influence of the planets.

CHAPTER XII

THE PLANETARY HYPOTHESIS OF SUNSPOTS

IN this chapter we shall continue the discussion of the origin of the sunspot period. Without further explanation I shall present the results of my own investigations, even where they closely resemble those of Mr. Clayton. The differences of method and of viewpoint are sufficient, it seems, to make both presentations worth while.

In testing the possible relation of the planets to sunspots my investigations have inevitably followed two of the lines already discussed by Mr. Clayton. In the first line of study an attempt is made to determine whether the sun's own rotation has any effect on the number of sunspots, that is, to see whether sunspots show any changes that are correlated with the position of different parts of the sun's surface in relation to the planets. The second is an attempt to determine how far the sunspots show periodicities corresponding to the periods of revolution of the planets. In the first attempt I have tried a modification of the method used by De la Rue, Maunder, Schuster, and Pocock. For every third day during the two sunspot cycles, 1889-1901 and 1902-1912, the *projected* areas of sunspots have been taken from the Greenwich tables. The projected numbers give the apparent areas of the spots seen on solar photographs without correction for the distortion due to the varying angles at which the spots are seen. Thus the spots in the center of the sun's disk appear at their full size. Away from the center they are foreshortened until on the margin even the largest spot is reduced to a mere line or else disappears. The purpose of using the projected areas is to give chief weight to the spots on a particular meridian of the sun and less and less weight to those farther away.

The weighted areas thus obtained have been tabulated according to the positions of the earth and the planet when referred to the sun's center. Beginning, for example, with a day when the earth and Mercury are on the same polar meridian, that is, at Mercury's perigee when the planet is almost between the earth and the sun, the solar photograph for that day shows the area of the sunspots on the part of the sun which would then be near midday if Mercury were illuminating the sun. Three days later Mercury in its rapid revolution has forged about 9° ahead of the earth. Thus the central meridian on the solar photography for that day lies about 9° east of the central meridian as seen from Mercury. In the course of 116 days, that is, during the synodic period of Mercury, we are thus able to determine the area of sunspots not only on the part of the sun which sees Mercury near the meridian, but on the parts where that planet is rising or setting or is in the nadir. In respect to the superior planets lying outside the earth's orbit we forge ahead so that we see their sunset meridian, then their midnight, and finally their sunrise. Curves showing what happens on the sun during the 25-day period of solar rotation are shown in Fig. 49. The left-hand end of each curve shows the solar conditions directly beneath each planet, that is, when the planet is on the solar meridian; the parts to the right show conditions at various hours up to the setting of the planets, their midnight, and their dawn, these terms being used as if the observer were on the sun and were watching the rising and setting of the planets and experiencing the corresponding ups and downs in the number of sunspots.

The interpretation of Fig. 49 is difficult. The curves disclose no special uniformity although three out of four display maxima near the two ends. In the average curve at the bottom these two main maxima appear strongly and are symmetrically placed, each being about 60° from the noon meridian of the planet as viewed from the sun, but a third minor maximum also appears. The correlation

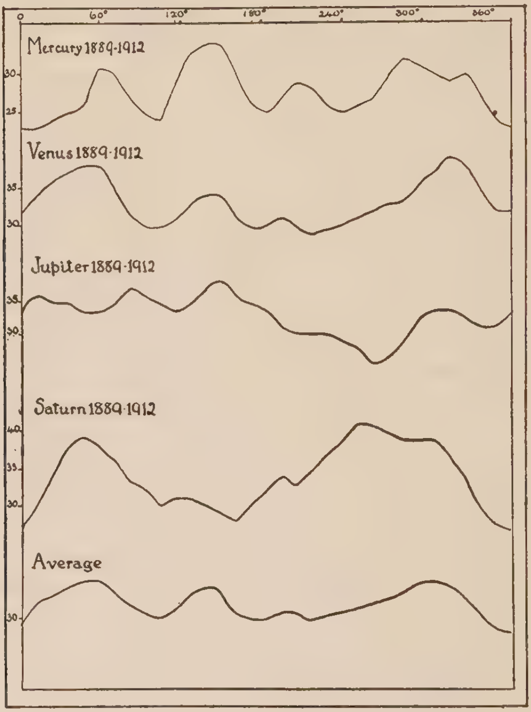

Fig. 49.

Sunspots in Relation to Solar Longitude of Planets, 1889-1912.

coefficients between the various pairs of curves are equally inconclusive. Arranged in order of their magnitude in proportion to their probable errors (r/e) they are as follows:

TABLE 28

CORRELATION COEFFICIENTS OF CURVES OF FIG. 49

	r	*e*	*r/e*
Saturn and Mercury	+0.056	±0.109	0.5
Jupiter and Mercury	+0.124	±0.106	1.2
Venus and Mercury	+0.226	±0.103	2.2
Jupiter and Venus	+0.222	±0.056	4.0
Saturn and Venus	—0.248	±0.056	4.4
Saturn and Jupiter	—0.586	±0.038	15.4

None of the three coefficients in which Mercury is a factor is significant. The other three, however, are four or more times as great as their probable errors, and therefore are significant according to the ordinarily accepted standards. Jupiter and Venus, it should be noted, are positively correlated, whereas these two planets when compared with Saturn give negative coefficients. This seems like a contradiction; and so it is if the relation between sun and planets is of a tidal nature, but not necessarily if the connection is electrical. In that case it may harmonize with the apparent contradiction already noted between Schuster's results and those of his predecessors, and may be due to differences in magnetic polarity. Thus while the investigation illustrated in Fig. 49 does not positively prove a connection between sunspots and planets, it agrees with much other evidence in indicating that we are face to face with a problem deserving of further study.

Let us now divide the data used in Fig. 49 into two parts according to the two sunspot cycles, 1889-1901 and 1902-1912. This is done in Fig. 50. If a planet causes sunspots

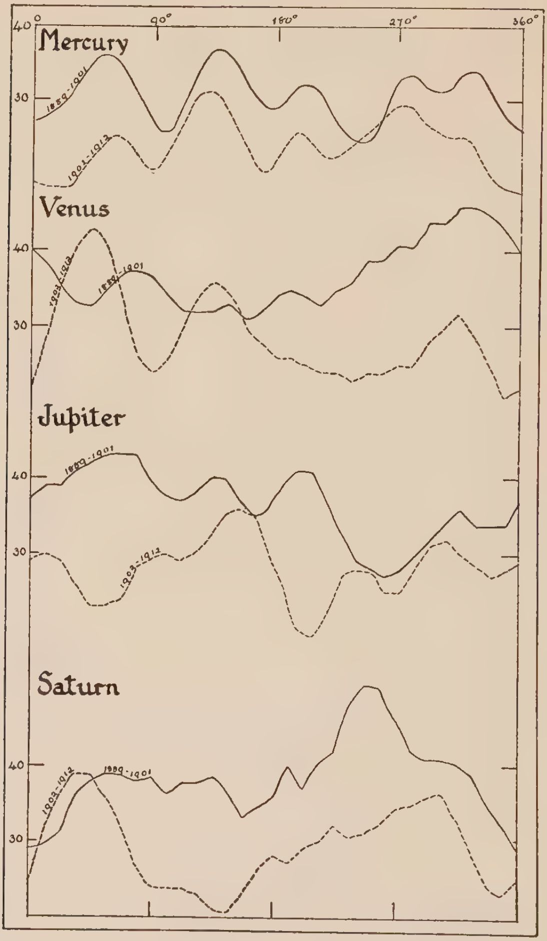

Fig. 50.

Sunspots in Relation to Solar Longitude of Planets during Two Sunspot Cycles, 1889-1901, and 1902-1912.

to increase in number when it is in a certain position with respect to a given meridian, we should expect the curves for the two sunspot cycles to be similar. The correlation coefficients of the several pairs of curves are given in Table 29. Mercury's two curves show similarity to a fairly high degree, and those of Saturn somewhat, while Venus shows a significant negative correlation and the two curves of Jupiter show no significant relationship.

TABLE 29

CORRELATION COEFFICIENTS OF CURVES OF FIG. 50

	r	*e*	*r/e*
1. Mercury	+0.493	±0.082	6.0
2. Venus	—0.364	±0.042	8.7
3. Jupiter	—0.135	±0.058	2.3
4. Saturn	+0.296	±0.056	5.3

Since the correlation coefficients for Mercury, Venus, and Saturn are all more than five times the probable error, there seems to be a real relationship. Apparently as the sun turns on its axis the number of sunspots in various solar longitudes varies irregularly according to the position of the planets. But why are there maxima in addition to the main maximum following the time when the planet is in the meridian? Why are the coefficients positive in two cases and negative in the other two? And why does Jupiter, the largest of the planets, show only an insignificant correlation?

The occurrence of maxima when the planets are at more than one angle with the solar meridian may be connected with variations in the sun's internal composition. Birkeland,[1] Bigelow,[2] and others have concluded that while the upper parts of the solar atmosphere may be of uniform composition, except when disturbed by eruptions from below, the deep-seated portions where the pressure is intense show differences from longitude to longitude. They believe that these differences may be analogous to the differentiation which in a far later stage of development caused the earth to be divided into segments, some of which formed the lands and the others the oceans. Possibly some of these areas are especially sensitive to planetary influence, but this is mere speculation. Another possibility is that an especially strong electrical effect is produced on the sun by the planets when the planets are situated at an angle of about 60° from the solar meridian on either side. In the lower line of Fig. 49 it appears that the sun's average relation to the position of all four planets during two sunspot cycles gives two main maxima when the planets are at these angles from the solar meridian. We have found that the electrical effects of the sun on the earth appear to be strongest when spots are at a considerable angular distance from the sun's meridian. If a similar electrical relationship prevails whereby the planets influence the sun, a similar arrangement would be expected. Even in Fig. 50, where accidental circumstances are clearly prominent, the majority of the maxima occur a little before and a little after the meridian passage of the planets; that is, somewhere near 60° from either end of the diagram.

The fact that the correlations between the pairs of curves in Fig. 50 are positive in two cases and negative in two is very perplexing. It certainly is not in harmony with a tidal cause, for there is no known way in which gravitation and tides can act in opposite ways at different times or in different places. On the other hand, an explanation may be forthcoming if the polarity of the sunspots were reversed at some time between the height of the sunspot cycle of 1889-1901 and 1902-1912. Such an assumption involves the further assumption that Mercury, perhaps because it is near the sun, and Saturn, perhaps because it is surrounded by rings, or is still more or less warm and gaseous, also suffered a change in magnetic polarity, while Venus suffered no such change, perhaps because it is permanently magnetized. Jupiter, being larger and presumably warmer and more gaseous than any other planet, may influence the sun through its own internal activities as well as through its position relative to the solar meridian. Such a supposition may possibly explain why the Jupiter curves of Fig. 50 for the two sunspot cycles show no significant correlation. All this, however, is pure speculation. The only positive result of the study illustrated in Figs. 49 and 50 is that six out of ten correlation coefficients rise to more than four times the probable error. This seems to indicate some real relationship between the activity of sunspots and the position of any given portion of the sun's disk in respect to the planets. The opposite signs of the coefficients, however, like the contradictions found by previous observers are highly puzzling. They seem to be out of harmony with a tidal hypothesis, but may perhaps accord with an electrical hypothesis.

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[1] Kr. Birkeland: *op. cit.*

[2] F. H. Bigelow: The Sun's Radiation and Other Solar Phenomena. A Meteorological Treatise on the Circulation and Radiation in the Atmospheres of the Earth and Sun.

Let us next investigate the relation of sunspots to the relative positions of the planets in their revolution around the sun. If the planets really disturb the sun's atmosphere we should expect the number of sunspots to change in harmony with the way in which the eccentricity of each planetary orbit causes that planet to vary in distance from the sun. In order to test this, we simply tabulate the number of sunspots by years, months, or days in such a way that the average sunspot number for any given position of the planet can be obtained. For example, for the earth we place the Januaries in the first column, the Februaries in the second, and so on. For Venus and Mars the process is the same except that the number of months in a revolution is about 7½ in one case and 23 in the other, and allowance has to be made for the fact that a revolution is not an exact multiple of the month. Such allowance is easily made by adding months just as a day is added to leap year. For Mercury, because its period of revolution is only 88 days, the *day* has been used as a unit, and the daily corrected sunspot areas as given in the Greenwich tables have been used instead of the Wolfer sunspot numbers which are employed in the other cases. For Jupiter and Saturn, because of the length of their periods of revolution, the year instead of the month has been taken as the unit. Saturn's period of revolution, 29 years, is so long that less than six revolutions have been completed since the beginning of even moderately reliable sunspot records. Hence it seems necessary to eliminate the large fluctuations which may be due to Jupiter, and thus free Saturn's effects from perplexing complications. Accordingly, the figures for Saturn have been smoothed by substituting for the original numbers the averages of 12 consecutive numbers. These averages have been placed in the positions of the sixth number.

Table 30 and Fig. 51 show the results. In both, the different planets have been reduced to the same scale by taking 100 as the average in each case. If there were no relationship all the curves would tend to become straight lines, and any departures from straight lines would be due merely to the fact that sufficient data were not available to smooth out all extraneous irregularities. Whatever irregularities remained would show an accidental and not a systematic distribution. What we actually find,

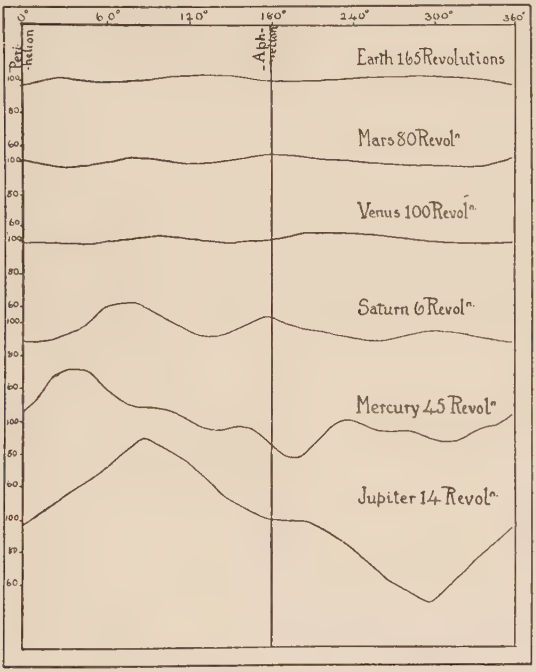

Fig. 51.

Sunspots during the Periods of Sidereal Revolution of the Planets. See Fig. 46.

however, is quite different. The earth, Mars, and Venus show relatively little relation to the sunspot cycle, while Saturn, Mercury, and Jupiter all show a pronounced maximum soon after perihelion. At first sight it may appear that this contrast between the two sets of planets is due to the much greater number of revolutions for which data are available for the upper set than for the lower in Fig. 51. This, however, does not apply to Mercury, for 45 revolutions are enough to eliminate the main accidental variations. Moreover, the data available as to times of sunspot maxima and minima previous to 1750 suggest that the curves for Jupiter and Saturn would not

TABLE 30

SUNSPOTS IN SIDERAL PERIODS OF PLANETS EXPRESSED IN PERCENTAGES OF THE AVERAGE

(The number of periods into which each sideral revolution is divided varies according to whether the day, month, or year is used as the unit. For example, the revolution of Mercury is divided into 30 periods of approximately 3 days each, and that of Jupiter into 12 periods of approximately a year each. Fractional parts at the ends of the periods are omitted in some cases, but this does not affect the results. In each case the entire body of figures represents 360°, as appears in Fig. 51. The first number in each column indicates the degree of solar spottedness when the planet is near perihelion.)

MERCURY

(Unit 3 days)
45 revolutions, Feb. 4, 1903-Nov. 18, 1908

Actual values	*Smoothed* values*	*Actual values*	*Smoothed* values*	*Actual values*	*Smoothed* values*
97	(103)	102	(101)	116	(100)
100	(113)	89	(96)	91	(96)
139	(126)	87	(94)	80	(93)
145	(132)	99	(96)	95	(93)
131	(130)	111	(95)	109	(93)
116	(121)	84	(87)	82	(89)
118	(114)	71	(79)	78	(87)
100	(109)	70	(78)	84	(89)
106	(108)	79	(86)	106	(95)
117	(106)	107	(97)	96	(97)
(Cont. in next columns)		(Cont. in next columns)			

* per $\frac{a+2b+3c+2d+e}{9}$

TABLE 30 (Continued)

VENUS (Unit 1 month) 100 revolutions Feb. 1840-July 1901	EARTH (Unit 1 month) 165 revolutions 1749-1913		MARS (Unit 1 month) 80 revolutions 1749-1901		JUPITER (Unit 1 year) 14 revolutions 1749-1915
99	Jan.	96.5	101	104	95
98	Feb.	101.5	98	104	113
103	Mar.	98.7	97	101	129
98	Apr.	99.7	99	100	149
105	May	102.1	102	99	136
103	June	102.0	101	98	113
99	July	99.4	99	97	100
	Aug.	99.7	100	97	98
	Sept.	100.2	102	97	83
	Oct.	101.3	(Cont. in next column)		62
	Nov.	101.2			48
	Dec.	100.6			71

SATURN

(Unit 1 year)
Approximately 6 revolutions, 1749-1918.

89	111	92	95	93
89	112	96	93	94
90	107	99	90	94
93	102	103	89	92
99	96	100	90	90
108	92	97	92	
(Cont. in next column)	(Cont. in next column)	(Cont. in next column)	(Cont. in next column)	

be flattened even if we could carry them back to 1600 A. D. It is worth noting that in each of the three curves where there is a well-defined maximum, it comes at an angle of from 36° to 90° after perihelion, that is, at about the time when one would look for a maximum effect because of nearness to the sun. In the same way the minima come at about the same angular distance after aphelion, as appears in Table 31. Such conditions suggest a real relationship for all the planets whose influence would be expected to be important.

TABLE 31

INTERVALS FROM SUNSPOT MAXIMA AND MINIMA TO PERIHELION AND APHELION

A *Planets*	*B* *Interval from perihelion to maximum, in degrees*	*C* *Interval from aphelion to minimum, in degrees*	*D* *Average*	*E* *Actual duration of interval D*
1. Mercury	36°	24°	30°	7 days
2. Saturn	84°	78°	81°	6½ years
3. Jupiter	90°	120°	105°	3½ years

As Clayton has already shown, and as we shall see more fully in the next chapter, Mercury, Jupiter, and Saturn are the three planets which would be expected to have the greatest influence upon the sun, and they are the three where the evidence of such relationship is most distinct.

One of the chief objections to the idea of a planetary cause of sunspots has been the difficulty of harmonizing the periods of the various planets and of the sunspots. Schuster[3] has analyzed the sunspot figures by one of the most reliable and critical methods yet evolved. Among the various periodicities which he finds, none corresponds exactly to any of the planets. By far the most noteworthy and persistent sunspot period formerly appeared to be 11.13 years, but the length of the cycle ending in 1917 raised this to 11.20. As this is about 6 per cent shorter than Jupiter's period of revolution around the sun (11.86 years), it has naturally been taken to militate strongly against any relationship. In fact, Schuster's method of analysis led Brown to abandon the planetary hypothesis in spite of the high correlation between his (Brown's) curve based on Jupiter and Saturn and the sunspot curve. Yet in spite of the difficulty as to periodicity Schuster later felt that other evidence pointed to a planetary hypothesis closely similar to that which his earlier conclusions seemed to negative. The reason for this confusion may be the extreme complexity of the planetary influences. They form an harmonic series involving not only the eight planets and perhaps other bodies, but also the eccentricities of the planets, and possibly their heliographic latitudes, as Arctowski has suggested.[4] Again, the sunspots are only one of many evidences of solar activity. A complete comparison of solar and planetary periodicities must embrace the entire activity of the sun's atmosphere, including prominences, faculæ, flocculi, the solar constant, magnetic activity, electrical activity, and perhaps other types not yet known. All of these seem to belong to a single great group of activities and may apparently replace one another, or at least react upon one another in such a way that no one of them is more than a rough indication of the true activity of the solar atmosphere.

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[3] A. Schuster: Phil. Trans., 1906, Vol. 206, p. 69; and Proc. Roy. Soc., Lon., Vol. 85, 1911, p. 50.

Wolf, Birkeland, Brown, and Clayton, as we have seen, have gone farther than most investigators in comparing sunspots and planets. Birkeland's combined curve of Jupiter, the earth, and Venus, shows a remarkable agreement with the sunspot curve, including numerous minor maxima. Unfortunately, he omitted Saturn, which appears to be second only to Jupiter in its influence on the sun's atmosphere. Brown, on the other hand, used Jupiter and Saturn. If his work and Birkeland's were combined, the result would agree with the sunspot curve more closely than does either curve at present. Nevertheless, in order to get the closest possible approximation to the sunspot curve it is necessary to use not only Jupiter, Saturn, Venus, and the earth, but Mercury, which seems to be decidedly important, Mars, Uranus, and Neptune, which are probably of slight importance, and perhaps other bodies. For instance, Schuster[5] and Turner[5] suggest that the Leonid meteors may have something to do with a period of about 33 years which is observable not only in sunspots, but also in climatic phenomena, as Brückner[6] long ago pointed out. The calculation of an harmonic curve depending on so many factors is so huge a task and some of the factors are as yet so little known, that mathematicians may well shrink from the attempt. It will take years of work.

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[4] H. Arctowski: Notice sur les fluctuations de la constant solaire, Mem. Soc. Spettr., Italiani, Vol. VI, 1917.

The sunspot curve appears to be dominated by some main cause which has a definite period, but the periodicity is often masked by other causes. As Newcomb puts it in one of his carefully considered papers: "Underlying the periodic variations of spot activity there is a uniform cycle, unchanging from time to time and determining the general mean of the activity."[7] This underlying cause seems to be Jupiter. Then the fundamental basis of the sunspot curve must be a period of 11.862 years. Even if this conclusion is correct, however, this exact period would rarely be apparent. Each of the other planets, and perhaps various other bodies, seemingly pull the maximum ahead at certain times and retard it at others. The irregularity which arises from the harmonic action of only two planets is evident in Brown's curve of Jupiter and Saturn in Chapter X, Fig. 41. If the number of disturbing bodies is greater, the effect becomes far more complex. When all the planets are used it is almost certain that sometimes the maximum may come at least three or four years earlier than it would if Jupiter were the only agent. A few decades later a retardation of similar duration may occur. Since 1788 the interval between sunspot maxima has ranged from 7.3 to 17.1 years. If the cycle is produced by the harmonic action of all the planets, there is reason to think that these are not the extreme limits, for almost innumerable complications are possible. In the intervals between maxima it must sometimes happen that several of the minor agents are in such positions that they combine to produce minor maxima of considerable importance. For example, a major maximum with a sunspot number of 174 in December, 1787, was followed by a minor minimum of 28 in April and of 11 in September, 1794; then came a minor maximum of 67 only two months later, and then the main minimum of 1798. Again in July, 1860, there was a maximum of 117; this was followed by a minor minimum of 22 in September, 1863, and then by a minor maximum of 66 in March, 1864. The great irregularity of the sunspot curve may be judged from Fig. 52. We shall see later that the combined effect of all the other planets is probably about equal to that of Jupiter alone. Occasionally it must happen that most of the other planets act together to produce a maximum somewhere near the middle of an unusually long interval between the maxima in which Jupiter has a part. The likelihood that such a maximum will be taken for the true maximum is great even at present, and was greater

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[5] A. Schuster: On the Periodicity of Sunspots, Proc. Roy. Astron. Soc., Lon., Vol. 85, 1911, pp. 50-53.

[6] E. Brückner: Klimaschwangkungen seit 1700, Vienna, 1891.

[7] Simon Newcomb: On the Period of the Solar Spots, Astrophysical Jour., Vol. 13, 1901, pp. 1-14.

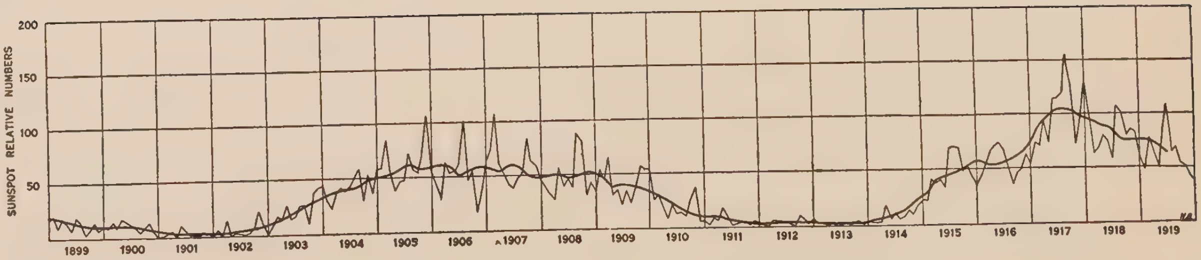

Fig. 52.

Observed and Smoothed Sunspot Relative Numbers, 1899-1919.

in the days when observations were scanty and when a relatively few large spots made much more impression upon observers than did a larger number of small spots.

Aside from specialists few people realize how much difficulty there is in determining the real dates when sunspot maxima or minima took place previous to about 1820. This is clear from Table 32, which gives the years at which sunspot minima and maxima took place, the weight which Wolfer attaches to each, the interval or period from minimum to minimum, and from maximum to maximum, and the sunspot numbers of the maximum calendar years. The weights are based partly on the character of the data, especially previous to 1750. After that date, however, the weights lose much of their value, because they depend partly on the degree to which the intervals depart from the standard length. Thus the minimum of 1784.7, which means seven-tenths of a year after the beginning of 1784, and the maximum of 1788.1 are given weights of only four, in part because the interval is surprisingly short, while the interval to the succeeding minimum is unusually long. This, however, merely reflects the general but possibly unwarranted opinion that the intervals ought to be approximately equal and should have a length of about 11.1 years. Back of 1750, however, the weights give a fair indication of the difficulty of knowing the exact sunspot conditions. Because of this difficulty it is possible that a secondary maximum may have been recorded as a main maximum. On the other hand, there is little chance that a main maximum has failed to be recorded since 1610 A. D.

Let us reconsider the length of the sunspot period. The ordinary way of determining it is to take the interval from the first reliable maximum or minimum, as given in Table 32, to the last maximum or minimum, and divide

TABLE 32

EPOCHS OF SUNSPOT MAXIMA AND MINIMA

Minima			*Maxima*			
Epoch	*Weight*	*Length of Period*	*Epoch*	*Weight*	*Period*	*Sunspot number*
1610.8	5		1615.5	2		
		8.2			10.5	
1619.0	1		1626.0	5		
		15.0			13.5	
1634.0	2		1639.5	2		
		11.0			9.5	
1645.0	5		1649.0	1		
		10.0			11.0	
1655.0	1		1660.0	1		
		11.0			15.0	
1666.0	2		1675.0	2		
		13.5			10.0	
1679.5	2		1685.0	2		
		10.0			8.0	
1689.5	2		1693.0	1		
		8.5			12.5	
1698.0	1		1705.5	4		
		14.0			12.7	
1712.0	3		1718.2	6		
		11.5			9.3	
1723.5	2		1727.5	4		
		10.5			11.2	
1734.0	2		1738.7	2		
		11.0			11.6	
1745.0	2		1750.3	7		83.4
		10.2			11.2	
1755.2	9		1761.5	7		85.9
		11.3			8.2	
1766.5	5		1769.7	8		106.1
		9.0			8.7	
1775.5	7		1778.4	5		154.4
		9.2			9.7	
1784.7	4		1788.1	4		132.0
		13.6			17.1	
1798.3	9		1805.2	5		47.5
		12.3			11.2	
1810.6	8		1816.4	8		45.8
		12.7			13.5	

TABLE 32 (Continued)

Minima			*Maxima*			
Epoch	*Weight*	*Length of Period*	*Epoch*	*Weight*	*Period*	*Sunspot number*
1823.3	10		1829.9	10		71.0
		10.6			7.3	
1833.9	10		1837.2	10		138.3
		9.6			10.9	
1843.5	10		1848.1	10		124.3
		12.5			12.0	
1856.0	10		1860.1	10		95.6
		11.2			10.5	
1867.2	10		1870.6	10		139.1
		11.7			13.3	
1878.9	10		1883.9	10		63.7
		10.7			10.2	
1889.6	10		1894.1	10		84.9
		12.1			12.3	
1901.7	10		1906.4	10		63.5
		11.7			11.2	
1913.6	10		1917.6	10		103.9

by the number of cycles. Up to a few years ago, as we have seen, the period was supposed to be 11.13 years, but the last sunspot cycle has raised this to 11.2, as calculated by Wolfer.[8] The results vary, however, as may be seen from Table 33.

It has often been asserted that there is no period in nature corresponding to the 11.2 years of the sunspot cycle. This assertion is questioned by See.[9] He believes that sunspots are due to the fall of meteoric matter upon the equatorial portions of the sun. This matter is assumed to follow orbits like those of the comets which have been captured by Saturn and especially by Jupiter. These comets move in the same direction as the planets and have their aphelia near the orbits of the planets and their perihelia near the sun. The interaction of the gravitative forces of the sun and the two planets must cause a certain number of the meteors to fall into the planets and a still larger number into the sun. Such an infall must generate a certain amount of heat and may cause other disturbances. According to a generally recognized law of dynamics such an influx of meteors near the equatorial plane of the sun must increase the speed of rotation in low latitudes. This is taken to be the reason why not only the sun, but both Jupiter and Saturn, appear to rotate faster at the equator than at the poles. By various methods See shows that

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[8] A. Wolfer: Mo. Weath. Rev., April, 1902, August, 1920, and January, 1923.

[9] T. J. J. See: Discovery of the Cause of the Sunspots, and of their 11-year Periodicity, and of the Cause of the Cepheid, Gemenid, and Cluster Variable Stars, Astr. Nachr. (Sondernummer), Band 216, August, 1922.

TABLE 33

LENGTH OF SUNSPOT CYCLE AS USUALLY ESTIMATED

Average interval between minima of 1610.8 and 1913.6	11.22 years
Average interval between minima of 1755.2 and 1913.6	11.29 years
Average interval between maxima of 1615.5 and 1917.6	11.19 years
Average interval between maxima of 1750.3 and 1917.6	11.15 years
Mean interval	11.21 years

> Jupiter's relative perturbative efficiency over Saturn's, in their mutual actions on meteors, whether moving with moderate or very great (parabolic) velocity, and thus not subject to appreciable change, is in the ratio of 1.828 to 1.
>
> Dynamically this means that whatever distance be taken as the unit of distance, and of action, Jupiter's sphere of influence and his efficiency, always is 1.82805 times greater than Saturn's.

In other words, if there be two periods based on meteor swarm precipitation,—namely, 11.86172 years, which is Jupiter's sidereal period, and 9.92945 years, which is the average period in which Saturn passes Jupiter's radius vector in the reverse direction at conjunction or at opposition—we must get their mean period by combining them with different weights as follows:

11.86172	wt. 1.82805
9.92945	1
Mean period=11.17846 years	

The amount by which this period departs from the mean sunspot period, as usually determined, is only about ten days, or a third of 1 per cent. Such an agreement is truly remarkable, and hardly seems like a mere coincidence. As the matter is worked out by See, however, the whole argument depends upon a meteoric hypothesis of sunspots. There are at least two objections to such an hypothesis which seem to make it highly doubtful, if not wholly untenable: (1) the arrangement of sunspots in latitudinal zones; and (2) the occurrence of the first spots in each cycle in relatively high latitudes. These will be considered in the next chapter.

In spite of the objections to a meteoric hypothesis based on the capture of swarms of meteors by Jupiter and Saturn, the closeness of the agreement of the Jupiter-Saturn period, as deduced by See, with the period ordinarily assigned to the sunspots can scarcely be ignored. If it really depends upon general principles instead of being wrapped up with the special hypothesis of meteors, it would be almost conclusive evidence of a connection between the sunspot period and the planets. As the matter now stands, however, we must suspend judgment.

This is the more advisable because the real length of the sunspot cycle, if indeed it has any absolute length, is not yet certain. As already stated, the sunspot cycle culminating in 1917 seemed to increase the apparent length of the cycle to 11.2 years. This result may be in error because of the uncertainty as to the exact dates of maxima and minima. At the beginning of the seventeenth century such uncertainty may rise as high as two years. Again, there is room for error because we do not know how much the maxima or minima that we employ have been retarded or accelerated beyond the date when they would have occurred if there were no cause other than the main one whose periodicity we are trying to find. According to Newcomb this uncertainty may amount to at least four years in either direction, or a total of eight if the first maximum, for example, were retarded four years and the last were accelerated by the same amount.

In order to eliminate these sources of error as far as possible, two methods may be pursued. One is to take the dates when sunspot activity was most pronounced; the other is to take dates as far apart as possible. When sunspots are at a maximum, it presumably means that the various agents which produce them are acting in close harmony. In that event the date of the maximum is not likely to depart far from the date when the main agent exerts its strongest effect. Moreover, the stronger a sunspot maximum, the greater the probability that its exact date will be determined correctly. The last maximum in 1917.6 may be reckoned as fairly pronounced, having a sunspot number of 103.9. Therefore we may start with it as our reference point. In the last column in Table 32 it appears that strong maxima occurred in 1870.6 with a sunspot number of 139.1, in 1837.1 with 138.3, and in 1778.4 with 154.4. Farther back, the sunspot numbers are not known and we cannot tell in which years the greatest maxima occurred. There is, however, a possible exception, namely, the year 1372. Chinese records, as explained in *Climatic Changes,* make it fairly certain that this was a year of remarkably numerous sunspots. The length of the sunspot period as deduced from the various major maxima, including 1372, as well as the most pronounced maxima since accurate records have been kept, is shown in column D of Table 34.

TABLE 34

LENGTH OF THE SUNSPOT PERIOD AS DERIVED FROM MAJOR MAXIMA

A *Dates of major maxima*	*B* *Interval to 1917.6 in years*	*C* *Number of cycles*	*D* *Average length of sunspots*
1870.6-1917.6	47.0	4	11.750
1837.2-1917.6	80.4	7	11.486
1778.4-1917.6	139.2	12	11.600
1372.0-1917.6	545.6	46 (47)	11.861 (11.608)
1778.4-1870.6	92.2	8	11.525
		Average	11.644

We do not know the number of cycles between 1372 and 1917.6. If we assume that there have been 49 cycles, the average period is 11.135, but this is shorter than the period as calculated in the usual way in Table 33. On the other hand, 48 cycles give 11.366 years, or more than the ordinary supposition. If we assume 46 cycles, the period is 11.861 years, which is almost identical with Jupiter's period, 11.862. If there were 47 cycles from 1372 to 1917, the average length is 11.608, which comes very close to the other intervals in Table 34.

It is noteworthy that in column D all the estimates of the sunspot period are decidedly larger than in Table 33, where a seemingly less reliable method was used. It may be significant that for the longest interval where both the date of the maxima and the number of cycles are known with considerable accuracy, that is, from 1778 to 1917, the apparent length of the sunspot cycle rises to 11.60.

TABLE 35

DATES WHICH WOULD CAUSE THE NEXT SUNSPOT MAXIMUM TO HARMONIZE WITH SEE'S HARMONIC PERIOD OF JUPITER AND SATURN (A=11.178 YEARS) OR JUPITER'S PERIOD OF REVOLUTION (B=11.862 YEARS)

Major maximum serving as reference point		*Date at which a sunspot maximum would cause the sunspot cycle to have an apparent length of*	
Date	*Sunspot number*	*A=11.178 years*	*B=11.862 years*
1778.4	154.4	1923.7	1932.6
1837.2	138.4	1926.6	1932.1
1870.6	139.1	1926.5	1929.9
	Average	1925.6	1930.5

If we omit the year 1372 as being too doubtful, the average length of the sunspot cycle as deduced from the major maxima employed in Table 34 is 11.590 years. This represents a departure of 2.3 per cent from Jupiter's period of revolution around the sun (11.862), a departure considerably greater than that of See's period from the usually accepted sunspot period. Table 35 illustrates how slight a variation in the next sunspot period would bring the average intervals since three of the greatest recorded maxima into harmony with See's period on the one hand and Jupiter's on the other. If the next sunspot maximum should occur from 1925 to 1927, See's conclusion as to the harmonic period of Jupiter and Saturn would be strengthened, whereas a maximum in 1929 to 1931 would point toward Jupiter's period of revolution as the basic factor in the sunspot cycle. Neither 8 nor 12 years is a highly uncommon duration for a sunspot cycle, so that these suppositions are not unreasonable. Brown's harmonic diagram of Jupiter and Saturn suggests a maximum in 1931.

As the matter now stands this chapter seems to show that each new investigation brings to light new evidence of an apparent relation between sunspots and the planets. The great stumblingblock of the difference between the supposed length of the sunspot period and the period of Jupiter's revolution around the sun does indeed still remain. But its force is less than was supposed, for See's period may be correct, or our estimates of the length of the sunspot cycle on the basis of the major sunspot maxima may be correct. The problem is still full of complexity and perplexity, but the weight of evidence seems more and more to indicate a planetary hypothesis of sunspots.

CHAPTER XIII

THE NATURE OF PLANETARY INFLUENCE ON THE SUN

THE probability that the planets have some relation to sunspots seems sufficient to warrant an inquiry into how they exert their influence. Three agencies have been definitely suggested in this connection, namely, meteors, gravitation, and electrical emissions. None of these seems quantitatively sufficient. Nevertheless, a discussion of them may stimulate further research.

The meteoric hypothesis, as developed by See, assumes that clouds of meteors have been captured by Saturn, Jupiter, and the sun, in the same way in which comets are known to be captured. The normal orbit of the comets, and hence by inference of the meteors, is highly elliptical, with the sun at one focus. The aphelion portion of the orbit, where it is farthest from the sun, is not far from the orbit of one of the planets. This is because the comets and meteors appear originally to have come to our system as visitors from space, and have been captured by the combined gravitation of the sun and a planet. As the comets and meteors revolve around the sun their paths are disturbed by the attraction of the planets, with the result that sooner or later the great majority either fly away again into space, or fall into one of the planets or the sun. The sun, because of its size, must gather to itself by far the larger number. When Jupiter and Saturn are in conjunction so that both are in line on the same side of the sun, they exert a maximum disturbing effect on the orbits of the meteors. A similar unusually large effect is produced when the two planets are in opposition, with the sun directly between them. The interval from conjunction to opposition is 9.929 years. Jupiter's effect in disturbing the orbits of the meteors must also vary because of the eccentricity of the orbit of that body, whereby it is nearer the sun at some times than at others. Jupiter's period of revolution, as we have seen, is 11.862 years. See believes that the disturbances of the meteoric orbits due to the revolution of Jupiter and its opposition and conjunction with Saturn cause unusual numbers of meteors to be precipitated on the sun, thus giving rise to the sunspot cycle. The extraordinary way in which the period thus derived, 11.178 years, agrees with the supposed sunspot period has already been described.

In spite of this agreement, the meteoric hypothesis seems to fail to fit the facts in two vital respects.

(1) Most of the comets, and presumably the meteoric swarms, which have been captured by Jupiter and Saturn revolve in orbits nearly in the plane of the orbits of the planets, and hence not far from the plane of the sun's equator. Accordingly, as See points out, the great majority of the meteors precipitated on the sun by the interaction of that body and the planets must fall near the solar equator, the greatest number being at the equator, with a gradual diminution in higher latitudes. Such an arrangement, however, does not harmonize with the scarcity of sunspots in the zone within 5° of the equator and their great abundance in two zones centering in about latitude 16°. Moreover, if meteors are the cause of sunspots, it does not seem reasonable that spots should never be observed in latitudes higher than about 40°, for

meteors other than those belonging to the planetary groups must fall into the sun.

(2) According to a law discovered by Spoerer, each sunspot cycle begins with a few spots in relatively high latitudes, 30° or more on either side of the solar equator. As the sun's activity increases, new spots break out nearer and nearer the equator, until at times of maximum intensity the average position is only a little more than 15° from the equator. Then as the cycle dies away the zone of chief activity falls to a latitude of 10° or less. Before the waning series of spots dies away in low latitudes, a new cycle begins in higher latitudes. Thus for a period which may sometimes be two or three years, there are two distinct zones of spots, one waxing in latitudes 25° to 35° and one waning in latitudes 5° to 15°. Such an arrangement does not seem to harmonize with a meteoric origin of sunspots, especially in view of the fact that the same zonal arrangement occurs simultaneously on both sides of the sun's equator.

The most probable form of the gravitational hypothesis has already been explained in a quotation from Chamberlin cited in Clayton's chapter of this book (Chapter XI). According to this hypothesis each planet creates two opposite cones of lessened gravitational pull on the sun's surface. These correspond to high tides. They are separated by a girdle of intensified gravitation corresponding to low tides. In the cones the weakening of the solar gravitation relieves the pressure on the sun's interior. Thus the forces of contraction due to cooling and also the increased gravitative strain in the girdle between the two cones, tend to cause the lower gases of the sun to move upward in the centers of the cones, somewhat as molten rock moves upward in a volcano. The upward movements are supposed to be the inciting cause of sunspots. According to this hypothesis, as is the case with almost every other, only a minute fraction of the energy of the sunspot comes from the original inciting cause. A slight release of pressure merely permits existing strains to pass the point of resistance. The upwelling of gases and their ejection to great altitudes is due to the sun's own internal energy.

The electrical hypothesis, as here developed, holds that the effect of the planets upon the sun must in a small way duplicate the effect of the sun on the planets. In previous chapters we have seen that solar electrons appear to influence atmospheric electricity and perhaps other atmospheric phenomena. Since the outer portion of the atmosphere of the earth and presumably of the other planets appears to contain large numbers of electrons, some of them are almost certainly shot back into space. Their effect on the sun is supposed to resemble on a very small scale the corresponding effect of solar electrical emissions on the earth. The very minute electrical effects thus produced upon the sun are supposed to release internal strains and thus permit the formation of sunspots, somewhat as in the gravitational hypothesis.

The numerical factors involved in the gravitational and electrical hypotheses are given in Table 36. Gravitation depends on the mass, mean distance, eccentricity, and period of revolution. The tide-making force of each planet, its gravitative effect on the sun, and the departures of these from the normal are also given, the earth in each case being reckoned as unity. The electrical effect of a planet, as will be explained more fully later, varies as the square of the radius and the fourth power of the temperature, and inversely as the square of the distance. It may also depend on the degree of atmospheric disturbance. Since temperature is highly important, the absolute

TABLE 36

THE PLANETS

	A	B	C	D	E	F	G	H	I	J	K	L
	Mass. Earth=1	*Mean distance Millions of miles*	*Diameter. Earth=1*	*Eccentricity*	*Period (years)*	*Inclination to plane of sun's equator*	*Ascending node in respect to plane of sun's equator (Heliocentric longitude)*	*Gravitative force on sun Earth=1*	*Difference between maximum and minimum gravitative force due to eccentricity*	*Tide-making force on sun Earth=1*	*Difference between maximum and minimum tide-making force due to eccentricity*	*Assumed temperature of surface turned toward the sun in degrees. C=absolute*
Mercury	0.045	36.0	0.38	0.2056	0.241	3° 21′	327°.9	0.30	0.26	0.78	1.11	500°
Venus	0.807	67.2	0.97	0.0068	0.615	3° 47′	253°.2	1.55	0.05	2.14	0.11	350°
Earth	1.000	92.9	1.00	0.0167	1.000	7° 10′	254°.4	1.00	0.06	1.00	0.12	300°
Mars	0.107	141.5	0.55	0.0933	1.881	5° 34′	262°.7	0.05	0.02	0.03	0.02	240°
Jupiter	314.50	483.3	11.14	0.0484	11.862	6° 00′	249°.2	11.57	2.21	2.23	0.65	900°
Saturn	94.07	886.0	9.38	0.0558	29.458	5° 25′	237°.9	1.03	0.21	0.11	0.05	600°
Uranus	14.40	1781.9	3.81	0.0471	84.015	6° 24′	254°.5			0.002		
Neptune	16.72	2791.6	4.40	0.0085	164.788	6° 21′	240°.9			0.0006		

temperature of the surface of each planet when exposed to the sun has been estimated in column L of Table 36 on the basis of the calculations of Poynting. In assigning temperatures for Jupiter and Saturn the best we can do is to assume that their low densities and thick atmospheres indicate that they are fairly hot. Nevertheless, most authorities state that they are not hot enough to emit light. This seems to mean that a temperature of about 600°C., or let us say 900° absolute, is about as high as can be assigned to Jupiter's outer portions; while Saturn, being smaller, is presumably cooler.

In estimating the value of the gravitational and electrical hypotheses, it may be well to begin with a quotation from Schuster.[1]

> A few words may be said on the *a priori* difficulties which may be felt in accepting a direct influence of a planet on solar phenomena. The tidal effect of the planets on the sun's outer shell, which has been suggested by several writers, is generally believed to be too small to be effective, but gravitational effects may be much increased if there is a layer surrounding the sun in which gravitation is to some extent counterbalanced by radiation pressure. Arrhenius, in the theories he advocates, assumes such a cloudy layer, which is kept in suspension by radiation. It is easy to calculate the residual gravitation which must remain, so that the particles may not part company with the sun, in which case they must behave like satellites circulating round the sun in his time of revolution. If r be the radius of the sun (6.97×10^{10} cm.) and v the velocity which a point of the sun's equator possesses in virtue of the sun's rotation round his axis (2.03 kilom. per second), the acceleration of a particle revolving with the sun is $v^2/r = 0.59$. By a numerical coincidence this is also the mean acceleration of the earth in its orbit round the sun.
>
> It follows that the residual gravitational action of the sun on

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[1] A. Schuster: The Influence of Planets on the Formation of Sunspots, Proc. Roy. Soc., Lon., Vol. 85, 1911, pp. 309-323.

its suspended clouds is to the gravitational force of the earth on these clouds, as the mass of the sun is to the mass of the earth, or 330,000 times as great. That the earth's gravitational attraction, small though it may appear to be at first sight, may yet be effective in its action, is shown by comparing it with the action of the moon on a body placed on the surface of the earth, which only amounts to the 288,000th part of the weight of the body. But when we compare the effect of the earth on the sun with that of the moon on the tide, the advantage is considerably in favor of the former, because it is not, like the tidal action, differential in its nature, having the same direction on both sides of the sun.

We are not, however, dependent on radiation pressure for a plausible explanation of a planetary action on the outer shell of the solar globe, which may be purely electrostatic. The expulsion of negative electrons from hot bodies must leave the solar clouds positively electrified. On the other hand, negative particles ejected from the sun must to some extent accumulate in the outer layer of planetary atmospheres. An estimate of the maximum electrostatic effect of the planets on the solar atmosphere is easily made, because the electrification of the planetary atmosphere cannot exceed a certain value without dissipation into space. If σ be the charge per unit surface of the atmosphere, the outward force on each electron carrying a quantity of electricity e will be $4\pi\sigma ec^2$, where c is the velocity of light. This cannot be greater than the weight mg of this particle, where m denotes the mass of the ion to which the charge is attached.

The whole charge (E) of the planet having a radius a is $4\pi\sigma a^2$, so that this maximum charge is determined by $\mathrm{E}ec^2=mga^2$. The electrostatic action of E on a charge e' at the surface of the sun, is $\mathrm{E}e'c^2/d^2$, if d be the distance between the two bodies and the gravitational attraction of the planet on a particle of mass m' is $m'ga^2/d^2$. We therefore reach the conclusion, that if the particles of the solar clouds have the same ratio (e'/m') as charged particles in a planetary atmosphere, the electrostatic effect of the planet is equal to its gravitational effect. It need hardly be pointed out that the charge of the outer layer of its atmosphere produces no effect at the surface of a planet unless the uniformity of its distribution is temporarily disturbed. The electrification may therefore be responsible for some variation, periodic or otherwise, but not for any average effects taken over long periods of time.

The action of planets on particles ejected from the sun or returning to it may affect in other ways a delicately adjusted balance such as that which seems both electrically and gravitationally to regulate the phenomena at the solar surface, but enough has been said to show that a plausible explanation of a planetary action on sunspots may be found without going beyond well-established processes.

Table 37, which explains itself, may assist in forming an estimate of the relative importance of different planets in their action on the sun. If the result depends on the number of elec-

TABLE 37

SCHUSTER'S TABLE OF THE PLANETS[2]

Planets	a	m	km/a^2	$k'm/a^3$	s
Mercury	0.387	2.0×10^{-7}	0.43	1.10	6.6
Venus	0.723	2.5×10^{-6}	1.53	2.11	16.9
Earth	1.0	3.1×10^{-6}	1.0	1.0	17.6
Mars	1.52	3.2×10^{-7}	0.04	0.03	9.4
Jupiter	5.20	9.52×10^{-4}	11.27	2.17	37.0
Saturn	9.54	2.86×10^{-4}	1.00	0.11	18.0
Uranus	19.2	4.42×10^{-5}	0.38	0.02	3.5

a=relative distance from sun.
m=mass of planet referred to sun.
k and k′ are constants adjusted so that the effect for the earth is unity.
s=angular diameter of planet, measured in seconds of arc, as seen at its mean distance from sun.

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[2] These figures differ somewhat from those given in Table 28 because of different estimates of the mass of Jupiter and also because Schuster has apparently included the moon with the earth.

> trons ejected by the sun and caught by the planet, we might expect the effect to diminish rapidly with distance. But if Jupiter exerts an influence comparable with that of Mercury, the law of action can hardly diminish more rapidly than according to the inverse third power. If Jupiter has an effect, mass or size must come into play. I have added the last column to show the relative position of the planets with regard to their size and distance, irrespective of mass.

At first reading, this quotation gives the impression that Schuster means that gravitation may act in some other way than by tides. This seems to be impossible. The sun's radiation pressure may enable the tidal effect of the planets to produce greater results than would be possible otherwise, but the nature of the results must be tidal, that is, a differential attraction of the various parts of the sun in accordance with their distance from the attracting body, and a consequent bulging on both sides of the sun. Schuster's statement merely leaves us the alternative between a gravitational or tidal effect, and an electrical effect. Let us endeavor to see how far the evidence supports or refutes either of these ideas.

At the outset it should be noted that in both cases it is not the *total* tidal or electrical effect with which we are at present concerned. The variations or departures from the normal are what count. The total strength of either kind of force will indeed determine the entire degree of activity in the solar atmosphere so far as that special type of cause is concerned. What we are dealing with, however, is a condition of changing activity during cycles of definite length. So far as such changing activity is due to gravitation it must arise from variations in either the absolute or the relative positions of the planets. Brown's curve, Fig. 41, to which we have so often referred, is designed to show how the combined pull of Jupiter and

Saturn departs from their average pull when account is taken, first, of Jupiter's varying distance from the sun because of the eccentricity of the planet's orbit, and second, of the extent to which Saturn would add to or diminish the effect of Jupiter, provided the outer planet does thus reënforce the inner when the two are in opposition as well as in conjunction.

In Table 36, columns I and K show the variations in the gravitative pull of the various planets and in their tide-making force because of the eccentricities of the planetary orbits, the earth's force in each case being taken as unity. In Table 38 these are rearranged in order of magnitude and the corresponding figures for variations in the probable electrical effect of the planets on the sun are added. This last column has been calculated on the assumption that the absolute temperature of the surface of the planets is as given in column L of Table 36.

This table affords an instructive comparison with Table 30 and Fig. 57, which show the effect of the different planets on sunspots as measured by the number of spots

TABLE 38

PERIODIC VARIATIONS OF THE PLANETS IN GRAVITATION, AND IN TIDE-MAKING AND ELECTRICAL FORCE

A Variations in gravitative pull of the sun		*B* Variations in tide-making force on sun		*C* Probable variations in electrical effect on the sun	
1. Jupiter	2.21	1. Mercury	1.11	1. Jupiter	700
2. Mercury	0.26	2. Jupiter	0.65	2. Mercury	100
3. Saturn	0.21	3. Earth	0.12	3. Saturn	35
4. Earth	0.06	4. Venus	0.11	4. Venus	1.7
5. Venus	0.05	5. Saturn	0.05	5. Earth	1.0
6. Mars	0.02	6. Mars	0.02	6. Mars	0.5

when the various planets are in perihelion, aphelion, and other positions along their orbits. Taking the difference between the maximum and minimum degrees of spottedness as there shown, we obtain Table 39, where the figures show the percentage by which the maximum number of sunspots exceeds the minimum when the spots are tabulated according to the position of each planet in its orbit around the sun.

TABLE 39

DIFFERENCES IN THE SUNSPOT NUMBERS AT MAXIMUM AND MINIMUM DURING THE PERIOD OF REVOLUTION OF THE PLANETS AROUND THE SUN

1. Jupiter	101
2. Mercury	54
3. Saturn	23
4. Venus	7
5. Mars	7
6. Earth	6

The resemblance between this table and column A of Table 38 is obvious at a glance. The only discrepancy is in the case of the earth. In other words, the variation in the spottedness of the sun during the respective periods of revolution of the planets is in almost complete accord with the variations in the gravitative pull of those same planets. The resemblance of Table 39 to column B of Table 38 is by no means so great as to column A, for in column B Mercury and Jupiter change places, and Saturn falls much below its position in the other table. Columns A and B, so far as they go, seem at first sight to support Schuster's suggestion that the sunspot periods may depend directly on the gravitative pull of the planets.

Column C of Table 38, however, shows that variations in the electrical effect of the planets agree with variations in the sunspots (Table 39) quite as closely as do variations in gravitation. In fact, the correlation coefficients between sunspots and the probable variations in the gravitative and electrical effect of the planets on the sun are, respectively, +0.92 and +0.93 (±0.04). This agrees with Schuster's conclusion that electrical and gravitative effects vary in the same ratios. It does not help to decide between the two, but it adds another bit of confirmatory evidence as to the reality of some sort of connection between the planets and sunspots.

Let us now inquire more specifically how the tidal and electrical hypotheses actually fare when applied to the sun. The gravitational hypothesis has much to recommend it, but it does not seem to harmonize with our study of the effect of the planets upon sunspots as given in the preceding chapter. We there found that the planets disagree among themselves and also disagree from one sunspot cycle to another. This seems unreasonable if the effect of the planets is primarily gravitational. Another difficulty is that, according to the tidal hypothesis, the maximum eruptive effect and hence the maximum sunspot activity ought to occur at the apexes of the tidal cones due to the various planets. The apexes all fall within 7° of the solar equator. Nevertheless, there are few spots within 7° of the equator. Moreover, the tidal hypothesis furnishes no mechanism by which the earlier spots of a given cycle appear in fairly high latitudes and the later spots in lower latitudes according to Spoerer's law. This is one of the most critical tests of any hypothesis and seems to be as fatal to the gravitational as to the meteoric hypothesis. Nevertheless, it does not seem wise entirely to reject either a gravitational or a meteoric hypothesis. Such complicated phenomena as sunspots, solar prominences, and the many other activities of the solar atmosphere are presumably due to a combination of many causes, just as are the movements of the earth's own atmosphere. In that case, a tidal cause may play some part even though other causes are equally important.

Turning now to the electrical hypothesis, we find that it fits the facts as to sunspots in certain positive and peculiar respects. One of these is the zonal arrangement of the spots. As developed in respect to the earth, the hypothesis holds that the electrons received from space are deflected as they approach that magnetized body, and hence accumulate in special abundance in two zones, one on either side of the equator, the latitude of the zones depending on the intensity of the magnetization. On the sun the sunspots occur in two zones similar to the two zones of cyclonic storms upon the earth, except that they are in somewhat lower latitudes. Although the solar magnetic field is actually stronger than that of the earth, it is weaker in proportion to the size of the sun. Hence the deflection of the incoming electrons would not be expected to be so great as on the earth, and the sunspot belt might fall mainly in latitudes 10° to 30° rather than 30° to 60° as on the earth.

Another interesting fact in respect to an electrical hypothesis is that sunspots, cyclonic storms, and Birkeland's electrical vortices on his magnetized globes all appear to follow Spoerer's law. Birkeland, it will be remembered, found that when his globes were not magnetized the vortices distributed themselves irregularly over the surface. When a globe was magnetized the vortices grouped themselves in bands parallel to the magnetic equator, and as the magnetization increased the bands moved toward the equator. In Chapter V we found that Kullmer's maps of storminess in the United States and Canada seem to indicate that a given series of cyclonic storms begins in high latitudes, increases in strength, and then migrates to lower latitudes in accordance with the progress of the sunspot cycle. Clayton's study of other terrestrial phenomena points in the same direction. During the sunspot cycle the magnetization of the earth also varies, according to Bauer. On the sun, as we have seen, a new sunspot cycle begins in relatively high latitudes near 30°, increases to a maximum in about latitude 16°, and then dies out in latitude 5° or 10°. In all three cases—Birkeland's vortices, cyclonic storms, and sunspots—we appear to have similar phenomena, and all occur on magnetized globes whose degree of magnetization is known to vary.

The contradictions between the apparent effects of the planets upon sunspots during different sunspot cycles are another set of conditions which seem to be out of harmony with a meteoric or a tidal hypothesis, but may possibly be explicable on an electrical hypothesis. If the polarity of sunspots can change once, as in 1912, it presumably has changed at other times. Whether the entire magnetic field of the sun could change we do not yet know. That did not happen in 1912, but since hot bodies cannot be permanently magnetized, they may perhaps change their entire polarity under the influence of causes like those which induce the change in the polarity of the spots. In any event, the change in the polarity of the spots suggests a possible explanation of almost innumerable apparent contradictions in the relations of sunspots and planets. In studying the effect of the sun on the earth, we found that the northern solar hemisphere produced a different effect from the southern, and that the seasons when the two hemispheres produced their maximum effect were different. In other words, we discovered terrestrial contradictions which may be analogous to the solar contradictions discussed in the last chapter, where the positions of the planets were compared with sunspots.

In this connection it is of interest to mention certain puzzling relationships found by Arctowski.[3] He investigated the relation of sunspots to the revolution of the earth around the sun, and found some evidence of a connection between sunspots and our planet, just as other investigators have found. For our present purpose the important point is that for the years 1852 to 1913 he points out that Wolfer's sunspot numbers indicate two maxima, one in February, the other in July, as shown in column A, Table 40. In order to investigate the matter in another way, Arctowski took the areas of spots as given in the Greenwich tables from 1874 to 1913, and found maxima in February and September. At first sight this double maximum seems to be the result of chance, but Arctowski goes on to show that, as appears in columns D, E, and F of Table 40, the maximum in the first half of the year is due to spots in the sun's southern hemisphere, while that in the second half is due to spots in the sun's northern hemisphere. This is illustrated in Fig. 53, where the upper line shows the area of spots in all solar latitudes, the next the spots in the southern hemisphere, and the lowest those of the northern hemisphere. When the earth is at its maximum distance north of the sun's equator, a position which it reaches early in March, it seems to be associated with an excess of spots in the sun's southern hemisphere, while six months later, when the earth is south of the solar equator, an excess appears in the northern hemisphere. Or possibly we are dealing with a delayed relationship, such that a maximum of spots in the sun's southern hemisphere follows shortly after the maximum inclination of the earth's southern hemisphere

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[3] H. Arctowski: De l'influence de la Terre sur la frequence et la latitude heliographique moyenne des taches solaires, Memorie della Societa degl Spettroscopisiti Italiani, Vol. V, 1916, pp. 98-99.

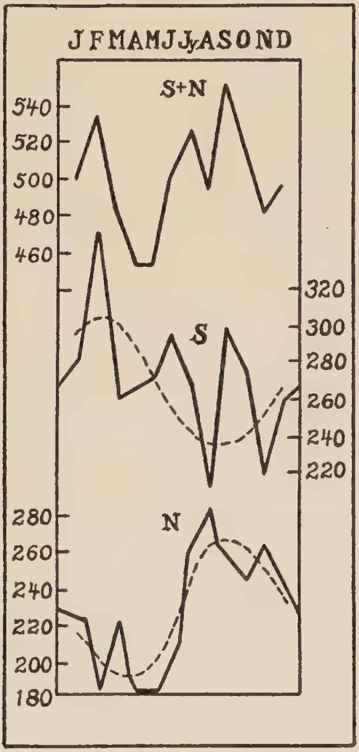

Fig. 53.

Arctowski's Diagram to Illustrate the Variation of Sunspots in Latitude during the Year.

s+n=area of spots in all latitudes, 1874-1913.
s=area of spots in southern solar hemisphere
n=area of spots in northern solar hemisphere

toward the sun; while the September solar maximum follows three months after the earth's northern hemisphere has been most strongly turned sunward.

The relationship appears to resemble that shown in

TABLE 40

SUNSPOTS IN RELATION TO THE EARTH'S REVOLUTION AROUND THE SUN

	A	*B*	*C*	*D*	*E*	*F*	*G*
	Average sunspot	*Wolfer number*	*Av. sunspot areas at Greenwich, 1874-1913*				
	1852-1913	1749-1913	*Total*	*S. Hemi.*	*N. Hemi.*	*Excess of S over N*	*Mean latitude of sunspots, 23 years*
Jan.	37.8	43.4*	501	280	221	59	*0.4° N*
Feb.	*42.3*	45.6	*535*	*351*	184	167	0.4° S
Mar.	42.0	44.3	484	260	*223**	37	0.4° S
Apr.	40.9	44.8	451*	267	184	83	0.1° N
May	40.7*	*45.9*	452	270	181*	89	3.2° S
June	40.7	45.9	504	205*	208	87	2.4° S
....	....	....	...	...	...	..	3.8° S*
July	*41.9*	44.6*	526	268	258	10	2.6° S
Aug.	41.6	44.8	495	213	*282*	—69	0.9° S
Sept.	40.5	45.0	*533*	*298*	255	43	*0.2° S*
Oct.	40.6	*45.6*	519	276	243	33	1.2° S
Nov.	39.2	45.5	481*	219*	262	—43	3.3° S
Dec.	37.5*	45.2	497	257	240	17	0.5° S

Figs. 37 and 38. There disturbances of the sun's northern hemisphere are seen to be associated with the production of gentle barometric gradients over the North Atlantic Ocean, which reach a maximum in April, May, and June; while spots in the sun's northern hemisphere are associated with the production of steep barometric gradients in September, October, and November. The essential point is that disturbances of the sun's northern hemisphere seem to be associated with times when the earth's southern hemisphere is turned sunward, while disturbances of the earth's northern hemisphere are especially associated with times when sunspots are active in the sun's southern hemisphere. The whole relationship is far too complicated to be unraveled as yet, but the mere fact that Fig. 53 shows a curious seasonal contrast resembling that of Fig. 38 seems to be one of many remarkable coincidences which suggest a mutual electrical reaction between the sun and the planets.

The conclusion reached by Arctowski carries with it the inference that the average latitude of the sunspots as a whole may shift slightly north and south in accordance with the movements of the earth in respect to the solar equator. This inference seems to him to be justified by the fact that the average latitude is most northerly in January, about four months after the earth's most southerly latitude, and most southerly about the end of June, some three or four months after the earth's most northerly position. The exact figures are given in the last column of Table 40. The extra number in the middle of the column, between June and July, is due to the fact that for this investigation it is necessary to use the period of solar rotation, averaging about 27 days in the sunspot latitudes, or over 13 to the year.

Turning to Venus, Arctowski[4] shows that the location of sunspots appears to be influenced by that planet also. Taking as his basis the solar rotations corresponding to various sections of the planet's orbit, he has prepared Table 41, which corresponds to column G of Table 40.

TABLE 41

MEAN LATITUDE OF SUNSPOTS DURING 54 PERIODS OF REVOLUTION OF VENUS

Section	I.	1.9 S
Section	II.	*3.1 S*
Section	III.	0.9 S
Section	IV.	0.3 S*
Section	V.	1.4 S
Section	VI.	1.4 S
Section	VII.	1.9 S
Section	VIII.	1.9 S

These figures are even more regular than those for the earth,—too regular to be accidental. They indicate that the greatest southerly mean latitude of spots comes a trifle after the time when the planet is in its most northerly position. The fact that when the earth or Venus is on one side of the solar equator, sunspots tend to increase on the other side, is another of the many puzzling facts which may possibly be explicable on an electrical hypothesis.

In this connection another line of investigation may be suggested. It has long been known that sunspots are not equally divided between the northern and southern hemispheres of the sun. Previous to about 1850 they appear to have been most numerous in the northern hemisphere; then during the four cycles from 1856 to 1898 they were more numerous in the southern hemisphere, the excesses as given by Newcomb[5] being approximately 238, 451, 955, and 710. Apparently now the southern excess is coming to an end and giving place to a northern excess. If sunspots really are initiated by planetary action, their slow swing in latitude may be due to a similar slow swing in the combined influence of all the planets and other wandering bodies which exert an effect on the sun. In Table 36 columns E and F have been inserted to assist future investigators in testing this suggestion so far as the planets are concerned. They were prepared by Miss Palmer of the Yale Observatory at the request of the director, Dr. Schlesinger. Other bodies, such as those which cause certain unexplained perturbations of Mercury, may also enter into the matter. The whole question is in the highest degree speculative, but it may suggest profitable lines of research.

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[4] H. Arctowski: De l'influence de Venus sur la latitude heliographique moyenne des taches solaires, Comptes Rendus, Vol. 163, 1916, p. 121.

Before leaving the subject of sunspots one important consideration must be emphasized once more. It is not to be supposed that the planets supply the energy displayed in sunspots and other movements of the sun's atmosphere. The energy derived from them may be, proportionally, no more than that of the pressing of a button which starts an explosion. When an electrical readjustment, a tidal current, a gravitational pull, a falling meteor, or any other cause once starts a little eddy, the slight movement thus generated may be reinforced by stresses due to the rapid cooling of the sun's outer layer, or to the sun's varying rate of rotation at different latitudes. When once in motion at any given level, a whirl may perhaps work upward into the higher portions of the solar atmosphere, and also penetrate deeper into the lower parts, and thus receive accessions of energy from regions below the isothermal layer. Thus while the electrical, tidal, and gravitational effects of the planets may be utterly insignificant so far as their own energy is concerned, they may perhaps start small movements which in turn draw on vastly larger stores of energy.

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[5] S. Newcomb: Astrophysical Jour., Vol. 13, 1901, p. 1.

In concluding this discussion of planetary influence upon the sun we shall sum up our three hypotheses as to possible ways in which outside bodies may affect the sun's atmosphere. The meteoric hypothesis has the advantage of conforming with the length of the sunspot period as usually reckoned. It likewise provides a perfectly definite and easily comprehended mechanism by which solar vortices may arise. It has the disadvantage of postulating conditions which do not agree either with the actual distribution of sunspots, or with their zonal migrations, their apparent relationships to the small planets as well as the large, and the contradictions from cycle to cycle and planet to planet. The gravitational hypothesis has the advantage of appealing to a well-known and well-defined method of action and of being in harmony with the variations in the magnitude of the apparent solar effects produced by different planets. One of its disadvantages is that the quantitative value of the force to which it appeals is very small and may be inadequate. Another is that it does not seem to be in harmony with the zonal arrangement of sunspots, with their latitudinal migration during the course of each cycle, and with the peculiar contradictions from planet to planet and from one sunspot cycle to another. The electrical hypothesis, through the agency of bipolarity and reversal, has the advantage of offering a possible explanation of the zonal arrangement, the latitudinal migration, and the apparent contradictions from planet to planet and cycle to cycle. Like the gravitational hypothesis it is in harmony with the differences between the apparent effect of one planet and another. Its disadvantages are that as yet its exact mode of action as set forth by Schuster is not perfectly clear, and its quantitative sufficiency is doubtful. Thus neither the meteoric, the gravitational, nor the electrical hypothesis can be definitely accepted as yet. Perhaps some wholly different hypothesis may offer the true explanation of the apparent connection between planets and sunspots.

This brings us to the end of this book, but not to the end of our investigation of the earth and the sun. That is continued in *Climatic Changes.* Although that volume appeared before this, it is really the second volume of *Earth and Sun,* and was written as such originally. In this volume we have seen that a study of sunspots reveals a number of ways in which solar activity appears to be closely related to the activity of the earth's atmosphere. This relation appears in the swing from high terrestrial temperature during periods of few sunspots to low temperature during periods of many spots. It appears in the number and location of storms, and in the variations in barometric gradients over the Atlantic Ocean. In all these respects a study of solar radiation as expressed by Abbot's solar constant discloses relationships similar to those of sunspots, as is fully shown in Clayton's *World Weather.* But there are other terrestrial conditions which seem to be correlated with the sun's electrical status rather than with its emission of ordinary radiation in the form of light. These terrestrial conditions include magnetism, auroras, earth currents, and atmospheric electricity, all of which appear to belong to one general series. One of them, atmospheric electricity,—and the same may be true of the others,—discloses a peculiar connection with certain parts of the sun's disk, a relationship which changes as a sunspot passes from one side of the disk to the other. Likewise the relationship in the sun's northern hemisphere is different from that in the southern hemisphere. All this is in accord with the bipolarity of sunspots, and suggests that the electrical and magnetic conditions of the earth are closely dependent upon electrical emissions which proceed largely from sunspots or from other areas which are electrified even though they present no visible signs of it.

The most unexpected feature of this book, at least to the author, is the discovery that the barometric gradients over the North Atlantic Ocean respond in different and opposed ways to sunspots on the two sides of the solar equator, and that one solar hemisphere shows a correlation with barometric conditions at one season and the other hemisphere at another season. These facts join with many others to suggest that the earth's atmospheric circulation is caused to vary in two ways, one—which is of main importance—being dependent upon the ordinary solar radiation, the other—and minor—being dependent upon the sun's electronic emissions. In this, perhaps, lies the explanation of some of the puzzling facts of meteorology and of the failure of many of our weather predictions.

The final step in the present book has been a study of the probable causes of sunspots. Here, too, the author is surprised at the result. The number of eminent scientists who have in one way or another advocated a planetary hypothesis is so large that their work cannot be overlooked, and each new investigation adds to the weight of evidence. Whether the planetary influence is gravitational, electrical, or of some other sort is far from clear;

but at least the ground is partly cleared for more intensive investigation.

The main conclusion of this book is that aside from the well-known phenomena of the seasons, variations in the atmospheric activity of the earth arise from variations in the solar atmosphere, regardless of their cause. In *Climatic Changes* this last conclusion is applied to the climate of the past, and solar activity is correlated with the other main factors which have altered the earth's climate from age to age. The present is taken as the key to the past. In *Earth and Sun* we have tried to describe the key and to show how it works. In *Climatic Changes* an attempt is made to turn the key and open the door.

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PRINTED IN THE UNITED STATES OF AMERICA

Date Due

APR 2 4 1952
MAR 2 8 1956
MAR 2 8 1956
Mar 14 '57
APR 3 1957
7 - 1958
MAR 2 9 '60
APR 2 2 '60
JUN 1 '60
JA 3 0 '65
FE 1 7 '65
MR 1 7 '65
JAN 1 5 1969
JAN 1 7 1970
DEC 1 0 1970
OCT 1 9 1971
OCT 2 8 1971
MAR 2 7 1977
MAY 2 2 1980
OCT 1 2 1980
OCT 2 1 1981
NOV 1 9 1982
MAY 2 5 1983
MAY 5 1984
MAY 2 2 1986

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Huntington, Ell - Earth and sun; an hypothesis of
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